The rate and pattern of bed incision and bank adjustment on the Colorado River in Glen Canyon downstream from Glen Canyon Dam, 1956–2000

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ABSTRACT

Closure of Glen Canyon Dam in 1963 transformed the Colorado River by reducing the magnitude and duration of spring floods, increasing the magnitude of base flows, and trapping fine sediment delivered from the upper watershed. These changes caused the channel downstream in Glen Canyon to incise, armor, and narrow. This study synthesizes over 45 yr of channel-change measurements and demonstrates that the rate and style of channel adjustment are directly related to both natural processes associated with sediment deficit and human decisions about dam operations. Although bed lowering in lower Glen Canyon began when the first cofferdam was installed in 1959, most incision occurred in 1965 in conjunction with 14 pulsed high flows that scoured an average of 2.6 m of sediment from the center of the channel. The average grain size of bed material has increased from 0.25 mm in 1956 to over 20 mm in 1999. The magnitude of incision at riffles decreases with distance downstream from the dam, while the magnitude of sediment evacuation from pools is spatially variable and extends farther downstream. Analysis of bed-material mobility indicates that the increase in bed-material grain size and reduction in reach-average gradient are consistent with the transformation of an adjustable-bed alluvial river to a channel with a stable bed that is rarely mobilized.

Decreased magnitude of peak discharges in the post-dam regime coupled with channel incision and the associated downward shifts of stage-discharge relations have caused sandbar and terrace erosion and the transformation of previously active sandbars and gravel bars to abandoned deposits that are no longer inundated. Erosion has been concentrated in a few pre-dam terraces that eroded rapidly for brief periods and have since stabilized. The abundance of abandoned deposits decreases downstream in conjunction with decreasing magnitude of shift in the stage-discharge relations. In the downstream part of the study area where riffles controlling channel elevation have not incised, channel narrowing has resulted from decreased magnitude of peak discharges and minor post-dam deposition. These physical changes to the aquatic and riparian systems have supported the establishment and success of an artifact ecosystem dominated by non-native species.

Models for the channel response downstream from large dams typically consider factors such as the degree of sediment deficit, the pre-dam surface and subsurface grain size, and the magnitude of post-dam average flows. These results suggest that it is also necessary to consider (1) the possibility of variable responses among different channel elements and (2) the potential importance of exceptional flows resulting from management decisions.

Keywords: channel adjustment, erosion, dams, geomorphology, alluvial deposits.

INTRODUCTION

Large dams, which are defined as those that impound more than 10^7 m^3 of water (Graf, 2005), cause changes to downstream flow and sediment supply that lead to changes in downstream channel form (e.g., Lawson, 1925; Stevens, 1938; Stanley, 1951; Borland and Miller, 1960; Petts, 1979; Lagasse, 1981; Galay, 1983; Williams and Wolman, 1984; Brandt, 2000a, 2000b; Simon et al., 2002; Hazel et al., 2006). Because large dams typically trap all sediment delivered from the upstream watershed, supply to the channel segment immediately downstream is virtually eliminated. The sediment mass balance of the downstream channel, which may have been in equilibrium, is, therefore, shifted into deficit. The magnitude of deficit depends on the change in sediment supply relative to the change in transport capacity. Large deficits extending over long river segments exist where transport capacity is little affected by impoundment and tributary sediment supply to the downstream channel is negligible (Schmidt et al., 1995). Small deficits or surplus conditions result where tributary supply is large and post-dam flow regulation reduces the downstream transport capacity (Andrews, 1986; Grams and Schmidt, 2002; Grant et al., 2003).

When the mass balance is shifted into deficit, evacuation of sediment occurs by export of bed and bank material. Here, we use the term *sediment evacuation* to describe the gross channel response to sediment deficit, and we use the term *bed incision* to specifically describe lowering of the bed, which is only one of the channel attributes potentially affected by evacuation. Distinction between these evacuation processes is especially important in systems where water-surface elevations are controlled at discrete locations by particular channel features, such as rapids or riffles. Thus, erosion of material from channel margins or pools between riffles that does not change the large-scale gradient is considered sediment evacuation, not incision. Incision has also been referred to as degradation (Pemberton, 1976) and retrogression (Stevens, 1938). Evacuation processes result in changes to the channel cross section, bed-material grain

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GSA Bulletin; May/June 2007; v. 119; no. 5/6; p. 556–575; doi: 10.1130/B25969.1; 16 figures; 2 tables; Data Repository item 2007089.

size, channel planform, and rates of channel migration. Bed coarsening provides a negative feedback that decreases transport rates, thereby slowing the rate of evacuation. Bed incision does not occur on every river subject to sediment evacuation, and a complete description of sediment evacuation processes must address changes in all attributes.

Bed incision and bed coarsening are predictable in many circumstances, and case studies demonstrate that (1) the rate of incision decreases with time as fine sediment is evacuated and the bed coarsens, and (2) the magnitude of incision typically decreases with increasing distance downstream from dams. Changes in channel width in deficit segments are typically variable. Bank erosion may result in channel widening (Williams and Wolman, 1984); however, reduced flood magnitude may lead to channel narrowing even under deficit conditions (Grams and Schmidt, 2005). Other changes associated with sediment deficit are less predictable, such as erosion of sandbars from eddies (Schmidt and Graf, 1990), or have not been described, such as the relative magnitude of evacuation from pools and riffles.

Efforts to systematically characterize the downstream effects of dams have included regression equations developed from empirical observations (e.g., Williams and Wolman, 1984; Brandt, 2000b), metrics based on the relative change in sediment supply and flow regime (e.g., Grant et al., 2003), and classifications (e.g., Brandt, 2000a). A general model capable of predicting the relative change of each attribute is not yet available. Future development and assessment of such a model will be based on case studies that describe all aspects of channel response in relation to changes in sediment supply and flow, and relatively few such case studies are available.

The 25 km segment of the Colorado River immediately downstream from Glen Canyon Dam is one regulated river where a comprehensive case study can be reported because detailed monitoring data that describe changes in streamflow, sediment flux, and channel attributes are available. Despite the richness of these data, they have not been summarized since Pemberton (1976) described the initial patterns of channel response that occurred during the first decade after dam completion. Many attributes of channel change have never been described. Here, we synthesize the complete record of change to the flow, sediment supply, and channel attributes during the interval between 1956 and 2000. We show that some attributes of channel change were anticipated and are predictable by the application of a simple physically based channel stability analysis, but changes of other attributes are less predictable and were not anticipated.

THE COLORADO RIVER IN GLEN CANYON

Characteristics of the River Corridor

Glen Canyon, named by Powell (1895), is one in the series of canyons carved by the Colorado River in its course across the Colorado Plateau. Extending over 200 km from Hite, Utah, downstream to Lees Ferry, Arizona, Glen Canyon is among the longest canyons of the Colorado River and includes hundreds of tributary canyons (Fig. 1). Except for the lowermost 25 km, most of Glen Canyon is currently flooded by Lake Powell, the reservoir formed by Glen Canyon Dam. In the upstream 21 km of the study area, bedrock from river level to the top of the canyon walls is Triassic to Jurassic Navajo Sandstone. In the downstream 4 km near Lees Ferry, bedrock is erodible Triassic conglomerate, sandstone, and shale.

Glen Canyon is an incised meandering canyon (sensu Harden, 1990) with a low average gradient, occasional small riffles, and few tributary debris fans. The Colorado River flows in a narrow alluvial valley; the average channel width for the post-dam 2 yr recurrence flood is 146 m, which is 80% of the average alluvial valley width of 183 m. The canyon walls are typically steep or vertical. The gradient is relatively flat; the average water-surface slope of the study area is now 0.0003. The river bed of the low-flow channel was once sand and is now gravel with minor patches of sand. Alluvial sand and gravel deposits line one or both banks.

Changes in sediment supply to the study area were primarily caused by completion of the dam because tributary drainages in this part of Glen Canyon are small. Webb et al. (2000) listed 32 ephemeral tributaries that join the Colorado River between Glen Canyon Dam and Lees Ferry. These tributaries drain a total of 291 km^2. The six largest (Fig. 1) tributaries drain between 14 and 92 km^2, and 20 tributaries drain less than 1 km^2.

Streamflow

The U.S. Geological Survey (USGS) gaging station, Colorado River at Lees Ferry, Arizona (station number 09380000), is located at the downstream end of the study area and has been in continuous operation since 1921. Before flow regulation, snowmelt floods typically peaked in May or June. Floods in tributary watersheds triggered smaller secondary peaks between July and October during the summer thunderstorm season. Partial regulation of the Colorado River in the study area began with closure of a cofferdam in February 1959, and complete regulation and filling of Lake Powell began with final dam closure in March 1963. Complete regulation reduced the 2 yr recurrence flood by 63% from 2407 m^3/s to 892 m^3/s (Topping et al., 2003), which is slightly less than the 940 m^3/s maximum operating capacity of the Glen Canyon power plant.

Since 1963, flows exceeded power plant capacity in 7 yr of the study period: 1965, 1980, 1983, 1984, 1985, 1986, and 1996 (Fig. 2A). In May 1965, the dam's river diversion tunnel, outlet works, and partially completed power plant were used to release a large volume of water downstream to Lake Mead in a short period of time. These releases consisted of 14 pulsed flows with durations of a few days to more than one week (Fig. 2C), and they were accomplished by increasing the stage in Lake Powell for periods of two weeks or less and then releasing a short-duration flood. The pulses increased progressively in peak discharge from 435 m^3/s in February to 1700 m^3/s in June 1965. After 1965, dam releases were at or below power plant capacity until the early 1980s when Lake Powell first reached full capacity. Soon thereafter, wet conditions in the Colorado River basin required use of the spillway, including a June 1983 release of 2755 m^3/s, the highest flow in the post-dam period. The high release of 1996 was part of management efforts to restore components of the river ecosystem in Glen Canyon and in Grand Canyon National Park, located further downstream (Webb et al., 1999).

Sediment Supply

Topping et al. (2000) reported the measured annual suspended sediment flux at the Lees Ferry gage for each sediment year between 1949 and 1970 (Fig. 2B). Sediment years are defined as the 12 mo between July 1 of the preceding year to June 30 of the indicated year. For the pre-dam period between 1949 and 1962, the average flux of fine sediment was $57 \pm 3 \times 10^6$ Mg (Topping et al., 2000). In sediment year 1963, which included regulated and unregulated flows, the measured flux was 20×10^6 Mg. The loads in 1964 and 1965 were 4.0×10^6 and 5.0×10^6 Mg, respectively. Between 1966 and 1970, the annual load averaged $0.24 \pm 0.01 \times 10^6$ Mg, more than 99% less than measured pre-dam loads (Topping et al., 2000).

Suspended load typically accounts for 90% or more of the total load of large continental rivers; this means that the magnitude of bedload transport is within the error of most measurements of suspended load (Meade et al., 1990). No measurements of bedload transport have been made in or near the study area in either the pre- or post-dam periods. However, the high measured rates of suspended sediment flux in the pre-dam

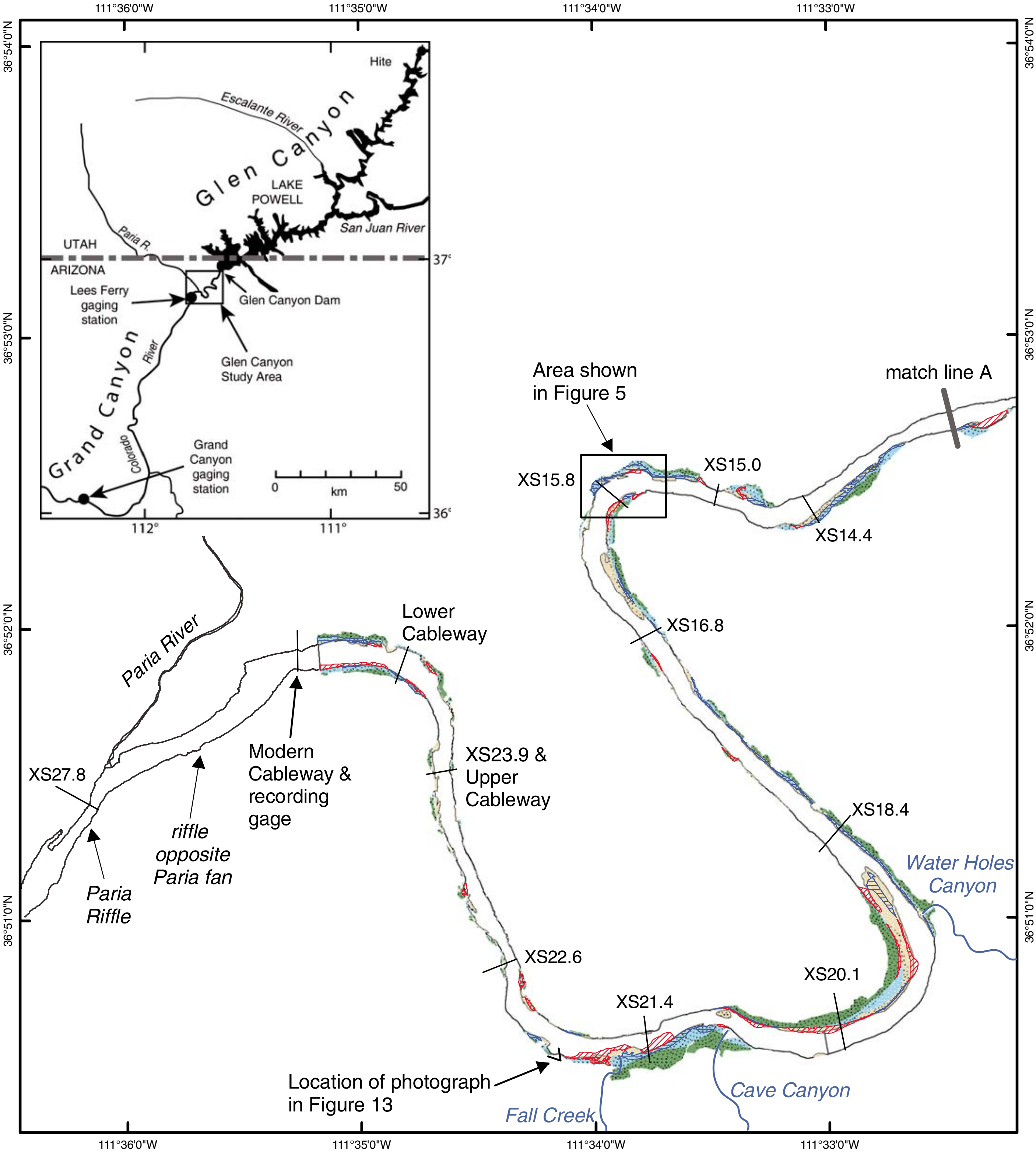


Figure 1. Glen Canyon study area and the distribution of alluvial deposits in 1984 and changes in deposits between 1952 (pre-dam) and 1984 (post-dam). The cross-section locations and largest tributaries are also shown. The cross sections are identified by their distance downstream from Glen Canyon Dam (in km). The projected coordinate system of the map is NAD83, Arizona State Plane, Central Zone (in m). (*Continued on following page.*)

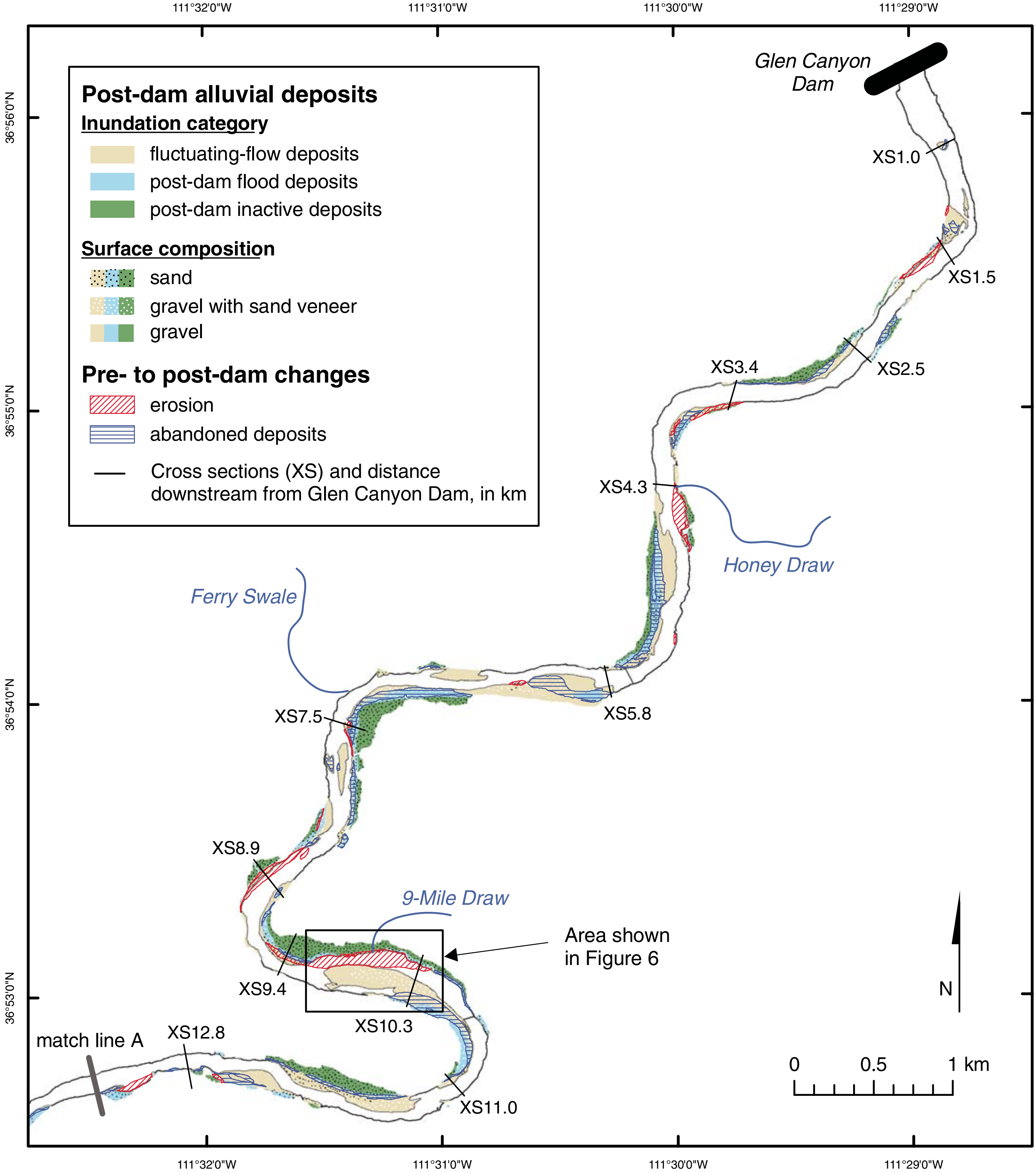


Figure 1 (*continued*). The shaded colors indicate the inundation frequency according to deposit categories, described in the text. The diagonal and horizontal cross-shadings indicate deposits that were either eroded or abandoned, respectively, between 1952 and 1984. The stippled patterns indicate the surface composition of the deposits. Dark stipples are sand, light stipples are gravel with sand veneer, and deposits with no stipples are gravel.

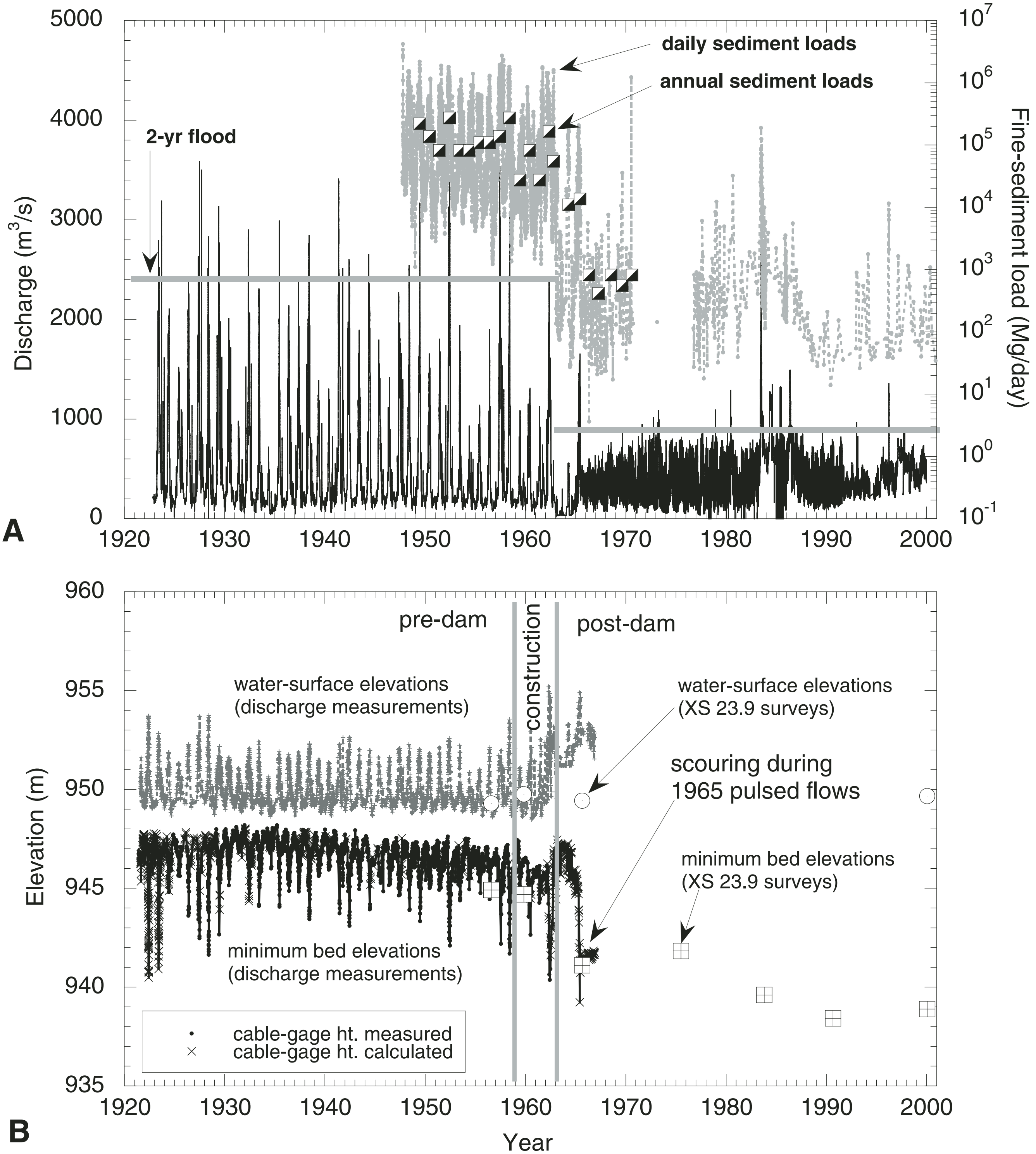


Figure 2. (A) Instantaneous discharge of the Colorado River at Lees Ferry, Arizona, 1921–2000, and measured sediment load for the same location, 1947–2000. The gray points connected by the dashed line are the computed loads for each day that sediment concentration was measured. The black and white boxes are the annual loads (expressed in Mg/d) computed by Topping et al. (2000) for the years with sufficient data. The thick horizontal line indicates the magnitude of the pre-dam and post-dam 2 yr recurrence flood. (B) Time series of water-surface elevations and minimum bed elevation for the Upper Cableway of the Lees Ferry gage from 14 August 1921 to 1 December 1966. Upper Cableway measurements for which the gage height was measured at the Upper Cableway are distinguished from measurements where only the recording gage height was measured and Upper Cableway gage height was calculated. Measurements made at the same location (XS 23.9) by Bureau of Reclamation and GCMRC are also shown. (*Continued on following page*).

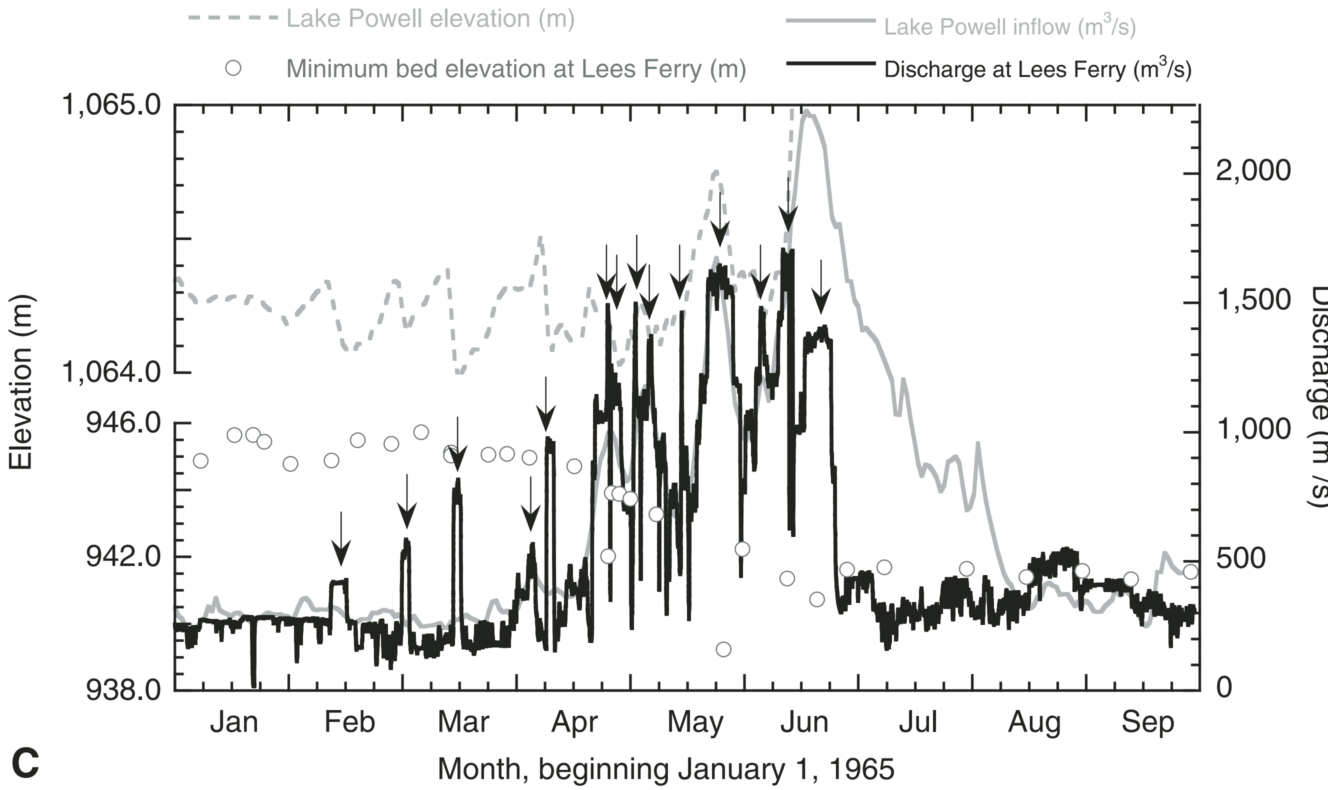


Figure 2 (*continued*). (C) Water-surface elevation of Lake Powell, the inflow to Lake Powell, the instantaneous discharge at Lees Ferry for the period of the 1965 pulsed flows, and the minimum bed elevation at Lees Ferry. The arrows indicate the timing of the 14 pulsed flows.

period together with the prevalence of suspendable material as active bed and bar forms along the Colorado River (Schmidt et al., 2004) support the assumption that suspension is the dominant mechanism of bed-material transport.

Because the Lees Ferry gage is at the downstream end of the study area, the post-dam measurements of suspended load reflect both tributary sediment inflow and sediment evacuation from the study area. However, the sediment load from tributaries to the study area and from hillslopes has not been measured. Based on estimates by Webb et al. (2000), the entire tributary drainage between Glen Canyon Dam and Lees Ferry delivers ~$0.06 \pm 0.03 \times 10^6$ Mg of fine sediment annually.[1] This suggests that, for the post-dam period when the flux past Lees Ferry was measured, sediment transport out of Glen Canyon exceeded the estimated tributary supply by a factor of 44 or greater in 1964 and 1965, and by a factor of three or greater from 1966 to 1970. These values indicate a sediment deficit between the dam and Lees Ferry that was accommodated by evacuation from the bed and/or banks of the Colorado River.

[1]Because of the large uncertainty associated with sediment delivery from ungaged streams, Webb et al. (2000) made estimates using three different methods. Here, we use the average of those three estimates, where the uncertainty is the difference between their maximum and minimum estimates.

Previous Studies of Channel Change

Before 1963, the annual spring snowmelt floods caused 2–7 m of scour at the Lees Ferry gage (Burkham, 1986; Topping et al., 2000). This season of sediment evacuation was typically followed by a season of sediment accumulation that began in summer and extended through fall. During the accumulation season, bed aggradation approximately balanced the preceding scour; thus, year to year changes in mean annual bed elevation were much smaller than the magnitude of bed elevation variation within each year. Beginning in 1929, the magnitude of fill in summer and fall was slightly less than the magnitude of scour of the immediately preceding flood, such that the mean bed elevation lowered 0.8 m by 1959 (Fig. 2B). Mean bed elevation decreased an additional 0.1 m between 1959 and 1963 (Topping et al., 2000). Burkham (1986) and Topping et al. (2000) concluded that the minor bed incision between 1929 and 1959 resulted from a gradual decrease in the upstream supply of sediment.

Pemberton (1976) summarized bed-elevation measurements made between 1956 and 1975 and compared them with predictions of bed incision made when the dam was being constructed (Bureau of Reclamation, 1957). The pre-dam study predicted that the depth and downstream extent of bed incision would be controlled by a gravel bar ~6 km downstream from the dam and by a gravel and cobble riffle located opposite the debris fan at the mouth of the Paria River (Fig. DR1[2]). Pemberton (1976) found that 9.87 $\times 10^6$ m^3 was evacuated from the 25 km study area by 1975, which was 20% more than had been predicted. Pemberton (1976) observed that the median grain size of armor on the surface of gravel and cobble bars throughout Glen Canyon was equal to or larger than the predicted armoring grain size, and he therefore concluded that continued bed incision was unlikely. Burkham (1986)

[2]GSA Data Repository item 2007089, copies of Bureau of Reclamation documents cited in the text, pre- and post-dam cross-section measurements, individual stage-discharge relations for each cross section, the discharge measurement data from the Lees Ferry gage, and the text of a 1935 quote from the Lees Ferry hydrographer, is available on the Web at http://www.geosociety.org/pubs/ft2007.htm. Requests may also be sent to editing@geosociety.org.

TABLE 1. LOCATIONS OF CROSS SECTIONS IN GLEN CANYON INDICATING WHICH CROSS SECTIONS WERE SURVEYED EACH YEAR AND THE DATES OF THOSE MEASUREMENTS IF KNOWN

Distance from dam (km)	Reclamation section ID	1956	1959	1965†	1975†	1983	1990†	2000
1.0	R-20	18 August	25 November	20–30 September	July	19 October	September	10 May
1.5	R-19	18 August						10 May
2.5	R-18	18 August	24 November	20–30 September	July	18 October	September	10 May
3.4	R-17	18 August						11 May
4.3	R-16	15 August	23 November	20–30 September	July	18 October	September	11 May
5.8	R-15	15 August	30 November	20–30 September	July	19 October	September	11 May
7.5	R-14	10 August	19 November	20–30 September	July	19 October	September	
8.9	R-13	10 August						27 January
9.4	R-12	10 August						27 January
10.3	R-11A	9 August	18 November	20–30 September	July	20 October	September	27 January
11.0	R-11	9 August						27 January
12.8	R-10	9 August	17 November	20–30 September	July	20 October	September	26 January
14.4	R-9	8 August						26 January
15.0	R-8	8 August	12 November	20–30 September	July	20 October	September	26 January
15.8	R-7	8 August						26 January
16.8	R-6	7 August						26 January
18.4	R-5	7 August	9 November	20–30 September	July	21 October	September	26 January
20.1	R-4	7 August						25 January
21.4	R-3	6 August						
22.6	R-2	6 August						25 January
23.9	R-1 (LFUC)‡	6 August	4 November	20–30 September	July	21 October	September	25 January
24.7	LFLC‡							24 January
25.4	LFMC‡							24 January
27.8	R-0	6 August	29 October	20–30 September	July		September	28 January

†Exact measurement date not known.
‡LFUC—Lees Ferry Upper Cableway; LFLC—Lees Ferry Lower Cableway; LFMC—Lees Ferry Modern Cableway.

showed that most of the bed-material evacuation at the Lees Ferry gage occurred during the May 1965 pulsed releases and that this scour persisted until 1984, which was the year of the most recent data that he analyzed. Williams and Wolman (1984) incorporated Pemberton's (1976) data into a general empirical relation describing the rate of bed incision at dams in the western United States, applied that relation to Glen Canyon, and predicted that bed incision would not stabilize until between 2023 and 2113.

DATA ANALYZED TO QUANTIFY CHANNEL CHANGE

Measurements of the River Bed

Bureau of Reclamation Monitoring Cross Sections

In 1956, the Bureau of Reclamation established 22 channel cross sections between the dam site and the Paria Riffle,[3] just downstream from Lees Ferry (Fig. 1). Eleven of these cross sections were selected as monitoring sites, and they were resurveyed in 1959, 1965, 1975, 1983, and 1990 (Table 1). In 2000, the USGS Grand Canyon Monitoring and Research Center (GCMRC) resurveyed 21 of these cross sections (Grams et al., 2004) (Table DR1, see footnote 1). Pemberton (1976) used the monitoring cross sections to estimate the volume of bed-sediment evacuation by calculating the change in cross-sectional area at each location and interpolating between cross sections. We repeated this calculation, including the measurements made since 1975. The volume of evacuated sediment was converted to mass assuming the eroded sediment had a specific gravity of 2.65 and a porosity of 35%. We also classified the channel at each cross section as either a riffle or pool on the basis of field inspection and local channel characteristics. Riffles were identified where channel depth was less than the study area average and average surface velocity was relatively high. Pools were identified where depth exceeded the reach average and surface velocity was relatively low.

Bureau of Reclamation also measured bed sediment grain size and thickness in 1956 (Pemberton, 1976). Surface grain size was determined at 10 locations; boreholes were drilled through the alluvium at seven locations; and, a jet probe was used to penetrate the fine sediment layer and determine the depth to gravel at nine locations. The bed-surface grain size was remeasured at 12 locations in 1966 by the Bureau of Reclamation and at 21 locations in 1999 as part of this study (Table DR2, see footnote 1). We reconstructed the longitudinal profile of the sand-gravel interface from these data. Stage-discharge relations were determined for each cross section using measured water-surface elevations and discharge at the Lees Ferry gage (Fig. DR2, see footnote 2). These data were divided into periods of stable stage-discharge relations by visual inspection and linear regression. Each period was determined by including the greatest number of sequential measurements that plotted with the same regression relation that had an R^2 value of 0.9 or greater.

Lees Ferry Gaging Station

Water surface and discharge have been measured at different locations (Fig. 1) since gaging began in 1921 (Topping et al., 2003). Water surface was measured at several staff gages between 1921 and 1923, and is currently being measured by a recording gage that has been at the same location since 19 January 1923. The Upper Cableway was located 1.5 km upstream from the recording gage and is at the same location as cross-section (XS) 23.9 (Table 1). The Lower Cableway was located 0.7 km upstream from the recording gage. These cableways were abandoned, and all discharge measurements since 13 December 1966 have been made at the Modern Cableway, 15 m upstream from the recording gage. Thus, it is not possible to assess changes in channel characteristics by simple comparison of pre-dam and post-dam discharge measurement records. We determined minimum bed (thalweg) elevation and channel width for each discharge measurement made at the Upper and Lower Cableways (Table DR3, see footnote 2) and integrated these data with minimum bed elevation measurements determined from the Bureau of Reclamation and GCMRC surveys of XS 23.9 (Upper Cableway) and the Lower Cableway. Measurements at the Upper Cableway provide the longest record of pre-dam bed elevations that can be compared with those of the post-dam period.

Prediction of Bed Stability

The magnitude of channel incision was examined by comparing measured channel characteristics with those predicted for a stable gravel-bed channel. This analysis focuses on the coarse fraction of the bed material, which was seasonally exposed in the pre-dam period and is the dominant bed material in the post-dam period. Although the movement of coarse bed

[3] The "Paria Riffle" as it is used here refers to a riffle that is formed by an unnamed tributary that enters the Colorado River about 1 km downstream from the mouth of the Paria River. This is the site of R-0, the most downstream cross section established by the Bureau of Reclamation. This riffle is distinct from the riffle that is opposite the fan formed by the Paria River, which is upstream from the Paria Riffle. The map used by the Bureau of Reclamation referred to the upstream riffle as the "Paria Riffle," but we follow the current usage and the convention established by published river maps (Stevens, 1938).

material by bedload transport likely represents a small fraction of the total sediment flux, the movement of this material affects the elevation of hydraulic controls and determines the rate of channel incision.

A threshold channel is defined as one where only minor transport occurs over a stable and mostly immobile bed, and an alluvial channel is one with a substantial sediment flux and a fully mobile bed. Prediction of the threshold state is based on the design principles for stable canals (Lane, 1955; Henderson, 1966) and uses the one-dimensional expressions for momentum, continuity, and resistance. The average boundary shear stress, τ, for conditions of steady, uniform flow was calculated using the one-dimensional form of the momentum equation

$$\tau = \rho g R S , \tag{1}$$

where ρ is the density of water, g is the acceleration due to gravity, R is the hydraulic radius, and S is the average water-surface slope. The average boundary shear stress associated with incipient motion of the bed material, τ_c, in nondimensional form, is the Shields parameter, or critical dimensionless shear stress, τ_c^*.

$$\tau_c^* = \frac{\tau_c}{(\boldsymbol{s}-1)\rho \boldsymbol{g} \boldsymbol{D}_{50}} , \tag{2}$$

where s is the specific gravity of sediment and D_{50} is the median grain size of the bed. Average flow depth h and mean cross-section velocity U are calculated by mass continuity and the Manning resistance relations, respectively,

$$h = \frac{Q}{BU} \tag{3}$$

and

$$U = \frac{\sqrt{S}}{n} R^{2/3} , \tag{4}$$

where Q is discharge, B is channel width, and n is the Manning's roughness coefficient. Equations 1 through 4 were solved iteratively for S for a range of grain sizes with specified discharge, channel width, and Shields parameter. Separate calculations were made using the pre-dam 2 yr recurrence flood and average channel width and the post-dam 2 yr recurrence flood and average channel width. The Bureau of Reclamation (1957) reported that Manning's n decreases from 0.03 to 0.02 as flow increases from 283 to 2832 m^3/s. We report results for the mean, minimum, and maximum of these n values. These relations define a stable-bed curve that relates grain size with the gradient necessary to mobilize the bed during pre-dam and post-dam average flood conditions. The curve suggests the range of likely combinations of bed-material grain size and gradient that, for a given channel geometry and flow, would result in a channel that would maintain a stable bed with little or no sediment transport.

Measurement of Alluvial Deposits

Pre-dam and Post-dam Maps of Alluvial Deposits in Glen Canyon

The cross-section measurements describe changes in bed elevation and allow analysis of incision and changes in gradient. However, cross-section measurements are inadequate for a spatially robust evaluation of changes of the banks and alluvial deposits, because few cross sections traverse channel-side deposits. To supplement the cross-section data, we measured changes in valley bottom deposits throughout Glen Canyon by mapping all alluvial deposits in the study area on photographs taken in 1952 and on six post-dam photograph series (Table 2).

TABLE 2. DATES OF AERIAL PHOTOGRAPHS USED IN SURFICIAL GEOLOGIC MAPPING AND THE DISCHARGE AT TIME OF PHOTOGRAPHY

Date	Scale	Discharge (m^3/s)	Portion of study area mapped†
14 September 1952	1:10,000	290	2.6 to 25
8 October 1952	1:10,000	180	0 to 2.6
21 October 1984	1:3000	141	0 to 25
2 June 1990	1:4800	141	0 to 25
11 October 1992	1:4800	226	0 to 19
30 May 1993	1:4800	226	19 to 25
24 March 1996	1:4800	226	0 to 25
4 April 1996	1:4800	290	0 to 25

†Given in km downstream from Glen Canyon Dam.

We classified the alluvial deposits by depositional facies, discharge of inundation, surface texture, and extent of vegetation cover. The map units are similar to those of Schmidt et al. (1999) and Hereford et al. (2000). The maps were digitized into a geographic information system using a digitizing tablet coordinated to stable features on the aerial photographs. Coordinates for the stable reference features were obtained from digital orthophotographs.

We determined the depositional facies of each deposit by interpretation of the photographs in stereo and by field inspection. Colorado River alluvial deposits were mapped as fine-grained eddy bars (Schmidt and Rubin, 1995), fine-grained channel-margin deposits, or gravel bars. Most channel-margin deposits are narrow river-parallel bar and bank deposits. We report the area of fine-grained deposits for each photograph series that we mapped.

The surface elevation of deposits cannot be measured by photogrammetric methods with sufficient resolution to detect topographic changes of alluvial deposits between years of photography. In lieu of absolute measurements of topographic change and in an effort to analyze changes in the entire study area in a spatially robust manner, we classified features by general categories of frequency of inundation and compared their distributions in 1952 and 1984. On the 1952 photographs, we mapped deposits in three inundation categories. Low-flow deposits consisted of sand and gravel that were visibly wet on the photographs, indicating that they had been inundated by the flows of ~450 m^3/s that immediately preceded the photographs (Fig. 3). We mapped bare sand and gravel as pre-dam flood deposits, which we inferred to indicate deposition or reworking by the 3483 m^3/s flood that occurred in spring 1952. The low-flow deposits were assumed to have been inundated by frequent flows with less than a 1 yr recurrence in the pre-dam period, while the pre-dam flood deposits were assumed to have been inundated by approximately the 2 yr recurrence flood. Deposits inundated by flows greater than the pre-dam 2 yr recurrence flood and covered by established woody vegetation were mapped as pre-dam terraces. This map unit was consistent with pre-dam terrace units mapped by Hereford et al. (2000).

Deposits on the 1984 photographs were divided into a similar set of categories based on the post-dam flow regime. Deposits below the 892 m^3/s stage were in a zone affected by normal power plant operations and were mapped as fluctuating-flow deposits (Fig. 3). Flows greater than power plant capacity have created post-dam flood deposits. Since flows that inundate these surfaces are rare, their recurrence of inundation is poorly defined but is at least 5–10 yr. The wetted channel and fluctuating-flow deposits comprise the post-dam active channel. The post-dam flood deposits are partially or completely covered with woody vegetation and comprise the post-dam floodplain. Alluvial deposits higher in elevation than post-dam flood deposits and lacking evidence of deposition in 1983 or 1984 were mapped as post-dam inactive deposits. These deposits have not been inundated by post-dam floods. This category includes pre-dam terraces that have not been eroded and some lower-elevation pre-dam deposits that are not inundated in the post-dam flow regime.

There is imprecision in the characterization of areas of erosion and deposition based on changes in inundation frequency, because inundation frequency does not only occur due to erosion or deposition. Inundation frequency also changes due to the reduction in the flood regime

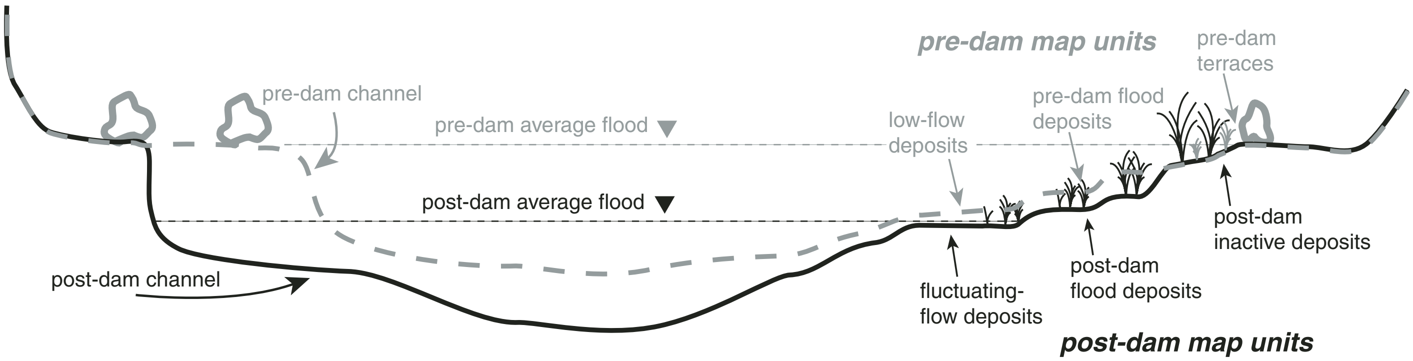


Figure 3. Sketch showing relative elevations of mapped deposits in relation to the pre- and post-dam channel. The approximate stages of the pre-dam average flood (2407 m³/s) and the post-dam average flood (892 m³/s) are shown. The post-dam average flood is at approximately the same elevation as the pre-dam channel bed. Vegetation on the post-dam deposits is mostly tamarisk, but other riparian species occur. Vegetation on the post-dam inactive deposits is mostly upland grasses and shrubs.

described already, and by bed incision and associated shifts in stage-discharge rating relations, described in the following. Where the change in deposit category indicated that the frequency of inundation increased from 1952 to 1984 (Fig. 4), we classified the area as having eroded, because erosion was the only mechanism by which the frequency of inundation could have increased. However, it is not possible to infer the cause of decreases in the frequency of inundation, because such a change might have resulted from vertical aggradation of the deposit, decrease in the flood regime, or downward shift in the stage-discharge relation caused by bed incision. Because the flood regime decreased, bed incision caused stage-discharge relations to shift downward, and there is little evidence for vertical aggradation, as described next, we believe that the dominant mechanism for decreased frequency of inundation was not associated with topographic change. Therefore, deposits where this style of change occurred were classified as abandoned (Fig. 4). In parts of the study area where incision did not occur, deposits classified as abandoned in the post-dam period may also be associated with minor deposition.

Interpretation of these topographic changes is consistent with measurements for similar periods at channel cross sections that traversed the same eddy sandbars (Fig. 5) and gravel bars (Fig. 6). For example, areas within the active channel in 1952 and mapped as fluctuating-flow and post-dam flood deposits in 1984 were classified as abandoned, rather than aggraded. Cross-section measurements at these locations indicated that no vertical aggradation had occurred. Comparison of inundation frequency interpreted from the 1952 and 1984 photographs on the river left side of XS 15.8 indicated that erosion had occurred, and cross-section measurements also showed erosion (Fig. 5).

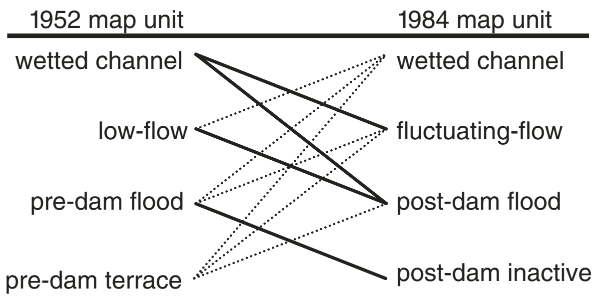
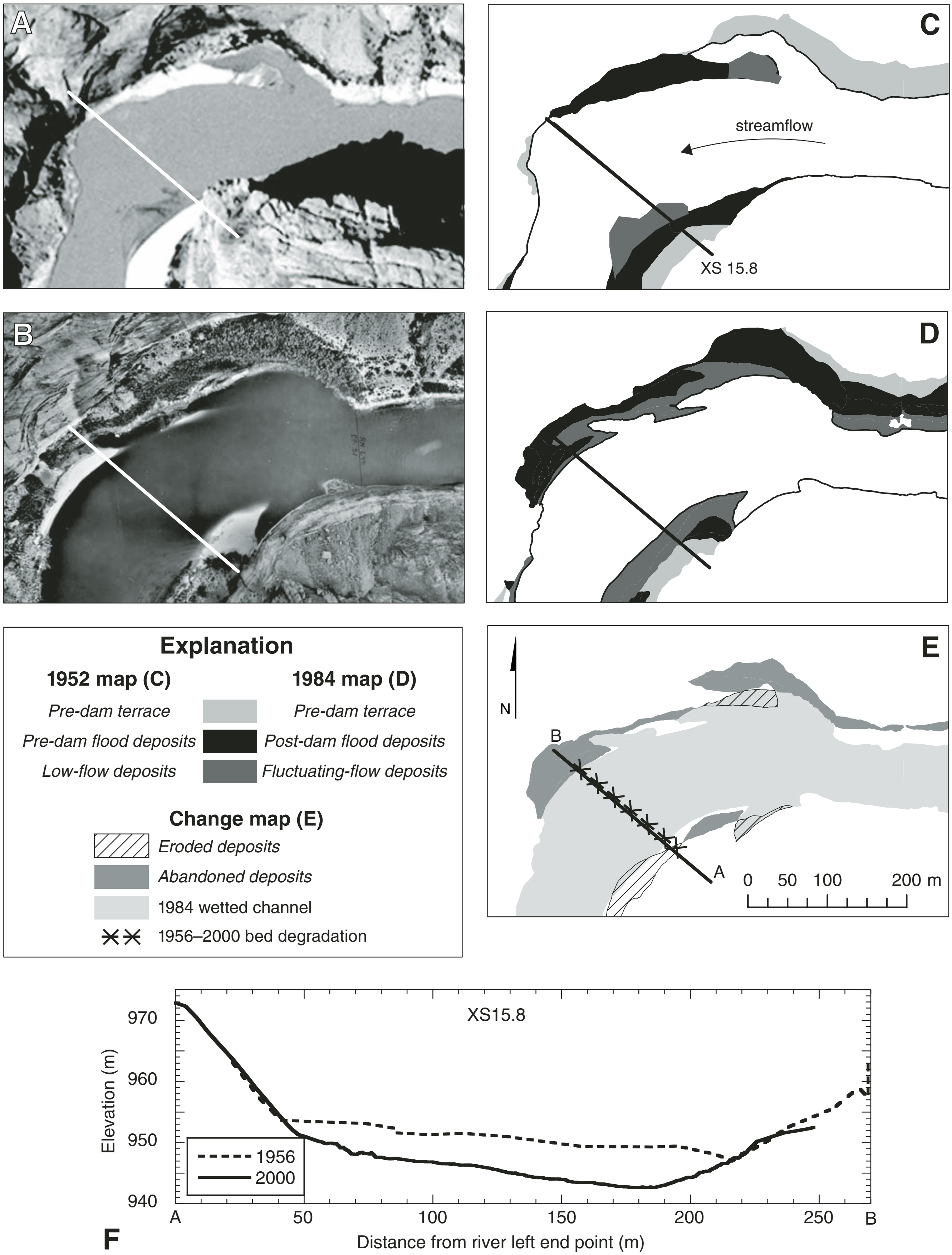


Figure 4. Trajectories of channel change between the 1952 and 1984 surficial geologic maps. Changes in map unit between 1952 and 1984 along the dashed lines indicate increased frequency of deposit inundation (eroded deposits), and changes along the solid lines indicate decreased frequency of deposit inundation (abandoned deposits).

Accuracy of the Surficial Geologic Maps. The process of creating digital maps from aerial photographs involves uncertainty, and we estimated the error associated with quantifying changes from one year of mapping to the next. The standard error in the reported area of each map unit was estimated by comparison with ground-based measurements. Schmidt et al. (2004) compared bar area determined from topographic survey with the area derived from aerial photographs for 26 sites in the Grand Canyon. We used the variance, σ^2, from these comparisons to calculate the standard error, SE, for the total area of each map unit for each year of map coverage as SE = $\sigma\sqrt{n}$, where σ is the standard deviation and n is the number of deposits surveyed.

The accuracy in change maps that are the product of an overlay of two input maps depends on mapping precision (Gaeuman et al., 2003). Uncertainty in the area of polygons that depict

Figure 5. Clips from aerial photographs taken in 1952 (A) and 1984 (B) and maps made from those photographs, respectively, (C) and (D) for the reach near cross-section XS 15.8, ~16 km downstream from Glen Canyon Dam. Interpreted changes in the channel-side deposits between 1952 and 1984 (E) are compared to the location of surveyed changes in topography along the cross section (F). Discharge was 290 m³/s at the time of the 1952 photograph and 141 m³/s at the time of the 1984 photograph. The abandoned deposits were entirely within the river channel in 1952 and were either fluctuating-flow or post-dam flood deposits in 1984. The survey of XS 15.8 in 2000 showed that the elevation of the surface of these deposits had decreased. In this location, the degrading deposit is associated with an increasing area of exposed sand and decreasing frequency of inundation. Note the bare sandbars and narrow strips of vegetation in the 1952 photograph. Streamflow is from right to left.


A
B
C
streamflow
XS 15.8
D
E
N
B
A
0 50 100 200 m
Explanation
1952 map (C)
1984 map (D)
Pre-dam terrace
Pre-dam terrace
Pre-dam flood deposits
Post-dam flood deposits
Low-flow deposits
Fluctuating-flow deposits
Change map (E)
Eroded deposits
Abandoned deposits
1984 wetted channel
1956–2000 bed degradation
F
XS15.8
Elevation (m)
970
960
950
940
1956
2000
A
50
100
150
200
250
B
Distance from river left end point (m)

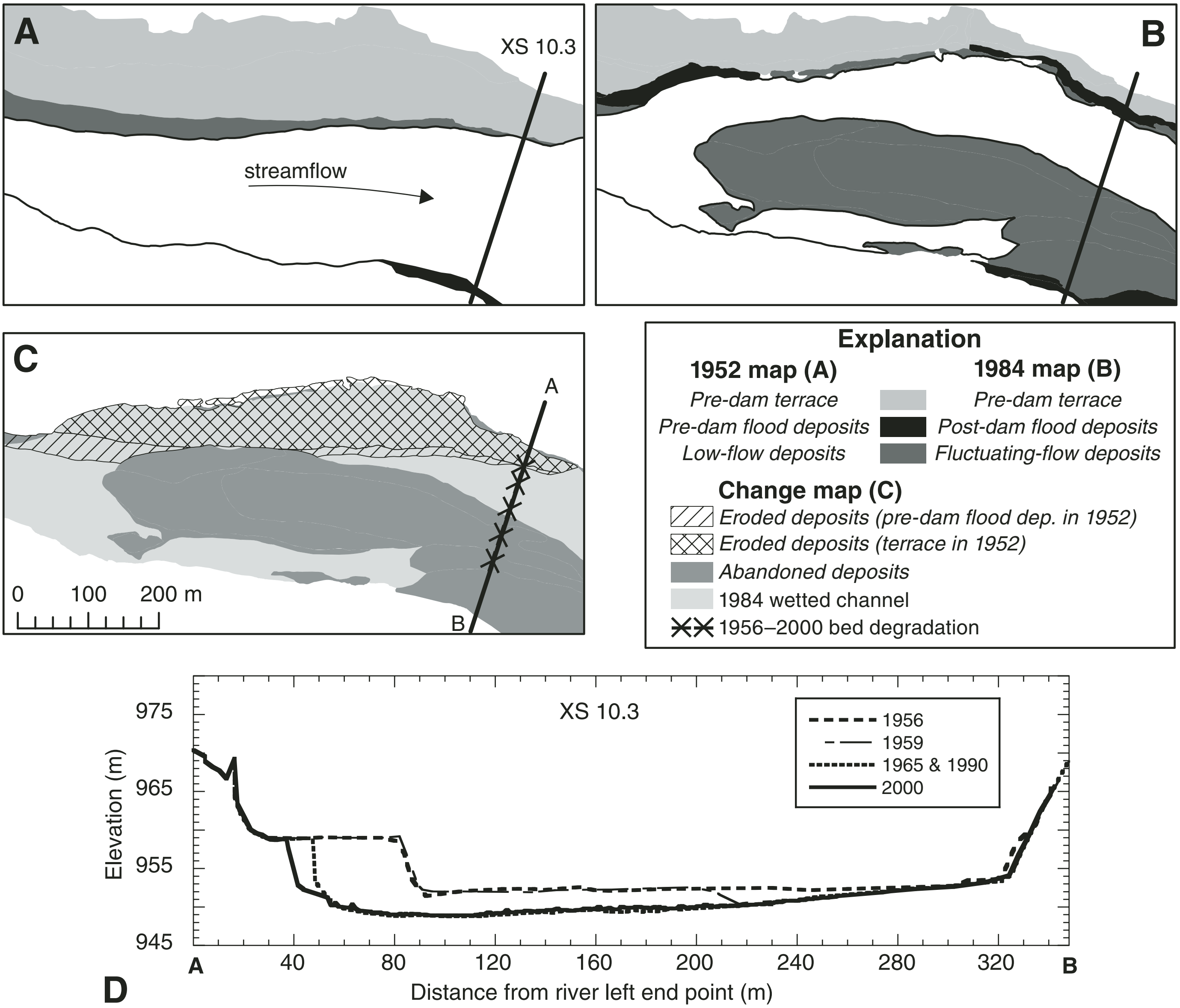


Figure 6. Maps based on the 1952 (A) and 1984 (B) aerial photographs and interpreted change (C) near cross-section XS 10.3 (D). Shows erosion of pre-dam terrace and adjacent pre-dam high-flow deposits on river left and abandoned deposits on river right. The abandoned deposit was the bed of the channel in 1952 and is currently an exposed gravel bar.

change was estimated as the product of the mean position error of the polygon and the perimeter of those polygons. Sondossi and Schmidt (2001) reported mean position error of 1.6 m between maps of Colorado River deposits made using methods similar to those used in this study. The total uncertainty in each map depicting change between two photograph series was calculated as the sum of the errors of the individual polygons. Because the proportional uncertainty is large for small polygons, polygons smaller than 500 m^2 were excluded from the analysis. The average uncertainty for all change maps was 9%, and it ranged from 5% to 14%. We used the larger estimate and rounded to 15% in our reported estimates of change between maps.

Channel Incision and Sediment Evacuation

The Timing and Magnitude of Sediment Evacuation

Limited sediment evacuation began during dam construction and was followed by accelerated evacuation during the 1965 pulsed flows. Bureau of Reclamation surveys show that some cross sections in the first 10 km downstream from the dam eroded between 1956 and 1959. During this period, the cross section 1 km downstream from the dam eroded ~3 m and other cross sections within 10 km of the dam eroded by smaller amounts. Cross sections more than 10 km from the dam were mostly stable before 1965 (Fig. 7). Between 1959 and 1965, the cross sections more than 1.0 km downstream from the dam eroded from 0.7 to 6.9 m (Fig. 7). The timing of sediment evacuation is precisely constrained only for XS 23.9, the Upper Cableway, where bed elevation was recorded in the near-weekly discharge measurements.

During the flow pulses of 1965, the bed at the Upper Cableway scoured deeper than any pre-dam measurement and never refilled to typical pre-dam elevations. The USGS measurements made between May 1965 and December 1966 show progressive net scour punctuated by two episodes of temporary accumulation during intervening low flows (Fig. 2C). At its lowest point, the thalweg elevation was ~6.5 m lower than in January 1965. By the conclusion of the flows, the thalweg elevation stabilized at an elevation ~4 m lower than the January measurement.

Following the 1965 pulsed flows, the rate of sediment evacuation declined sharply. Erosion rates were lowest between 1965 and 1975, when dam releases were maintained at or below power plant capacity. Between 1975 and 1990, some cross sections were stable while others (XS 1.0, XS 5.8, XS 7.5, XS 12.8, XS 15.0, and XS 23.9) continued to erode (Fig. 7). This erosion probably occurred during the high releases of 1983–1986. Between 1990 and 2000, dam releases were at or below power plant capacity and some cross sections located in pools were temporarily aggraded by as much as 1.5 m.

Measurements at the Upper Cableway show that bed elevations in that pool remained low and were never higher than 0.3 m above the elevation measured in December 1966. The persistence of low bed elevations and the fact that follow-up surveys were made during the season when pre-dam bed elevations were typically at their highest confirm that, despite temporary accumulations of up to 0.5 m, there were no long-term accumulations of bed sediment during the post-dam period. Thus, the scoured condition of the bed near the Lees Ferry gage has persisted for nearly 40 yr, and the cumulative magnitude of the scoured condition of this pool has increased. In January 2000, the bed was 2.2 m lower than the lowest elevation measured in 1965.

The sand bed surface and some underlying gravel were eroded in the process of sediment evacuation. At the time of the initial cross-section measurements in 1956, the bed was mostly sand, and the average bed-surface grain size was ~0.25 mm (Fig. 8). This sand was underlain at depths of up to 4 m by mixed sand and gravel that had a median grain size of ~20 mm. During evacuation, all of the sand and between 0 and 8 m of gravel was eroded from the bed (Fig. 9). Evidence for this style of evacuation can be directly evaluated at XS 4.3, XS 5.8, XS 12.8, and XS 16.8, where the depth to gravel in 1956 was measured at or near each of these cross sections. Approximately 50% of the material evacuated between 1956 and 2000 was derived from beneath the sand veneer.

We estimate that ~12.6×10^6 m^3 (21.6×10^6 Mg) of sand and gravel was evacuated between the beginning of dam construction and 2000 (Fig. 10). This amount exceeds the initial estimate of evacuation (Pemberton, 1976) by 2.7×10^6 m^3, or ~30%. According to the cross-section measurements, ~7.4×10^6 m^3 of this evacuation occurred between November 1959 and September 1965, and we estimate that 4.8×10^6 m^3 of this was evacuated between dam closure and September 1965 (Fig. 10). This estimate was reached by using the rate of evacuation measured between 1956 and November 1959 to estimate the rate of evacuation between November 1959 and March 1963. Because the 1959–1963 period had lower peak flows and lower suspended-sediment transport rates than the 1956–1959 period (Fig. 2A), this should provide a maximum estimate of evacuation for the final 3 yr of dam construction. Thus, 37% of the total evacuation measured between 1956 and 2000 and 64% of the evacuation that occurred after the dam was completed occurred between March 1963 and September 1965. Virtually all of this probably occurred during the 1965 pulsed flows, because dam releases between March 1963 and February 1965 were extremely low. A renewed phase of sediment evacuation occurred between 1983 and 2000, but at a lower rate than between 1956 and 1965.

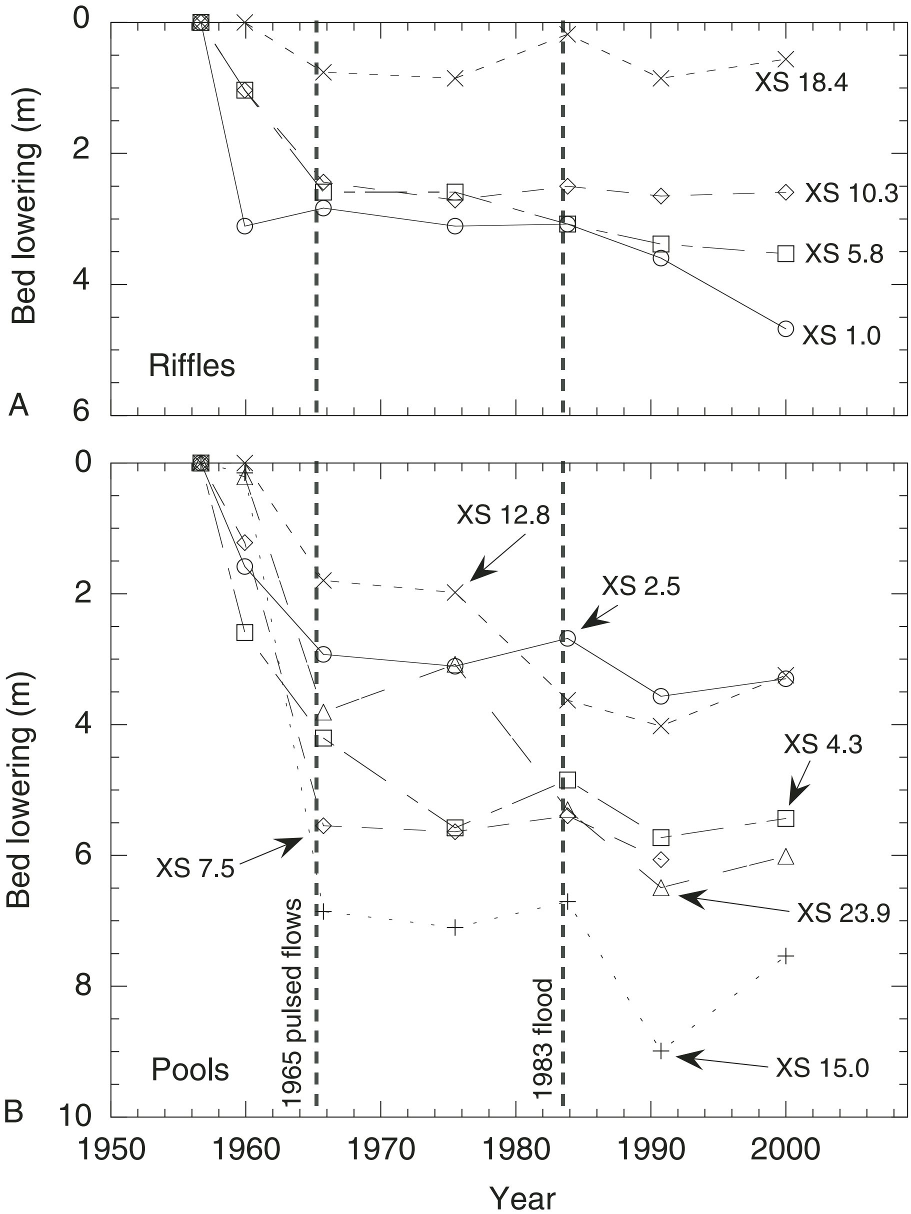


Figure 7. Magnitude of decrease in thalweg elevation from 1956 to 2000 at the 10 monitoring cross sections, grouped by riffles (A) and pools (B). Each cross section is labeled by distance downstream from Glen Canyon Dam, and the 1965 pulsed flows and the 1983 flood events are indicated.

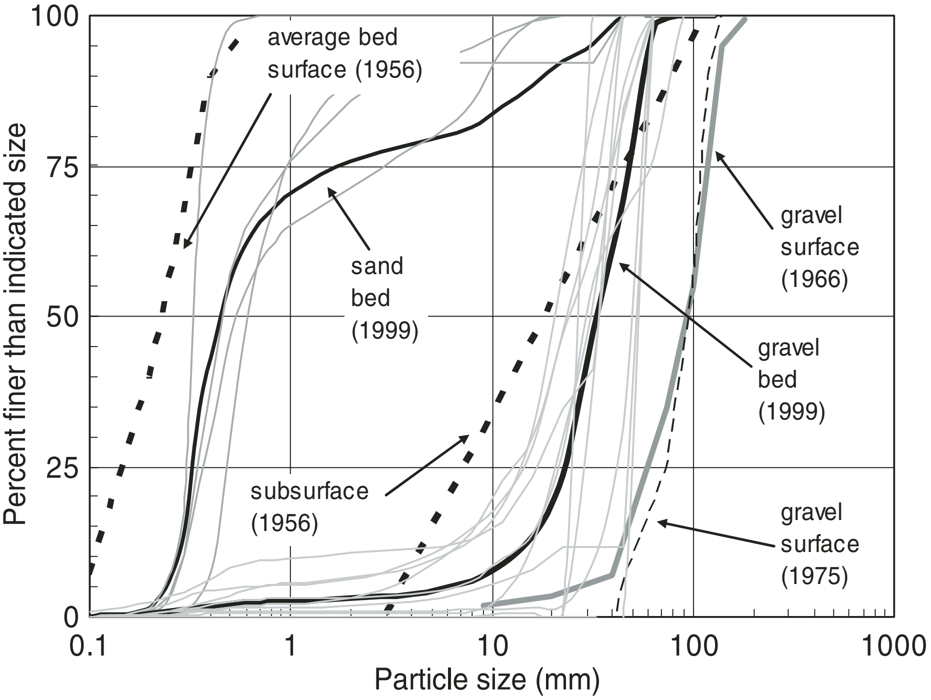


Figure 8. Bed-sediment grain-size distributions for Glen Canyon. The plotted distributions from 1956 include the average of bed-surface samples and the average of borehole samples of the underlying gravel layer (subsurface). Gravel bar surface samples are plotted for 1966 and 1975. The 1999 grain-size distributions are from samples collected by pipe dredge from a boat at ~1 km intervals throughout the study area. The 1999 samples are divided into those collected over a smooth bed (sand-sized material) and those collected over a rough bed (gravel-sized material). The thin gray lines show the individual samples, while the heavy black lines show the average of the respective sample groups. The 1956–1975 data are from Pemberton (1976). The 1999 gravel samples are finer than the 1966 and 1975 gravel samples because they were collected from the bed at regular intervals, while the earlier data were collected from selected exposed gravel bars.

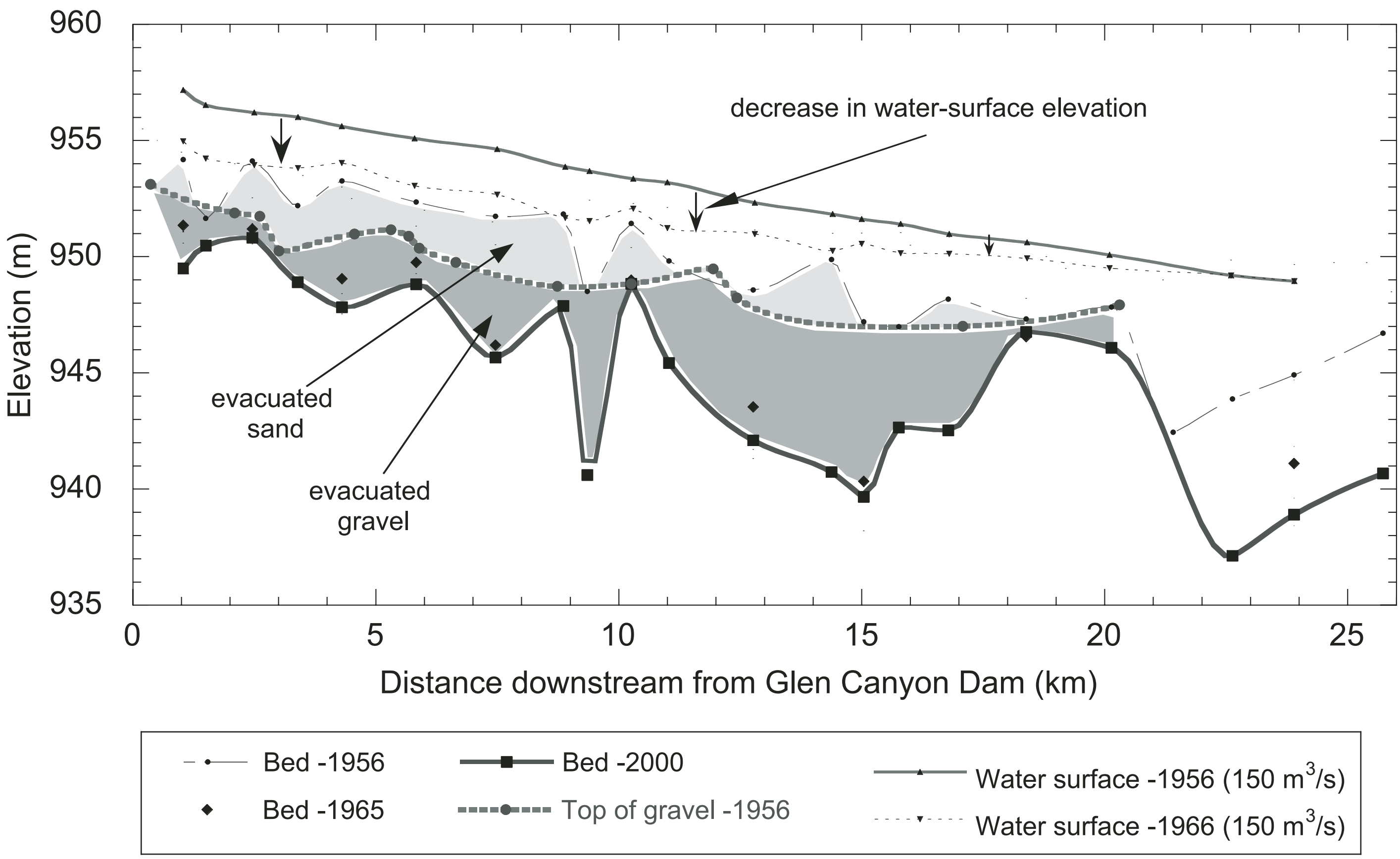


Figure 9. Longitudinal profile showing thalweg elevation for each of the Bureau of Reclamation surveys and elevation of the top of the gravel layer determined by borehole and jet probe measurements by the Bureau of Reclamation in 1956. Water-surface profiles for a common discharge of 150 m^3/s are also shown. For the distance of 7.5 km downstream from the dam, a measurement made in 1990 was used for the 2000 bed elevation because that station was not measured in 2000.

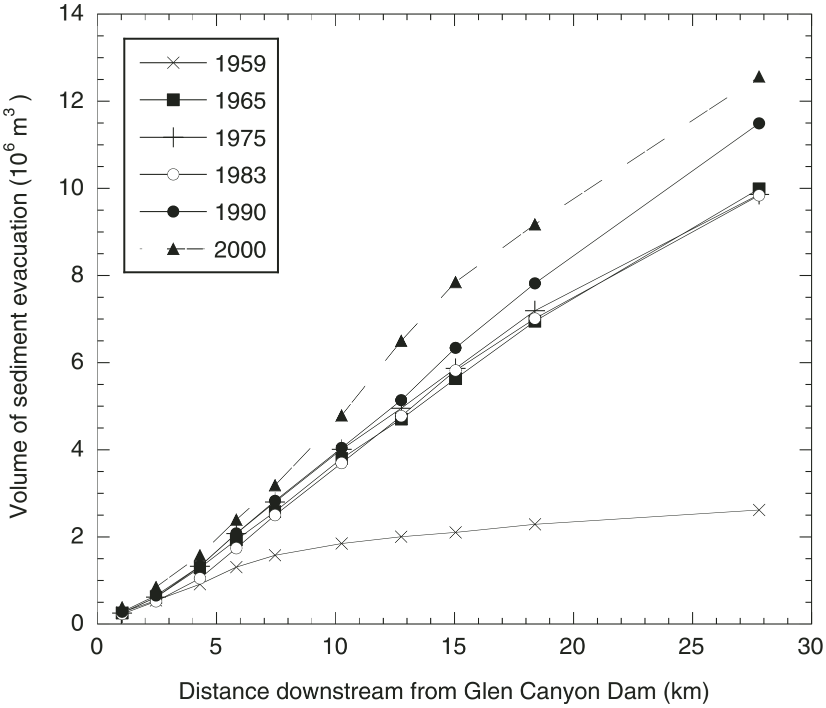


Figure 10. The volume of sediment evacuated from the bed calculated from the repeat measurements at channel cross sections. The volumes shown are accumulated by distance downstream from the dam and between the first measurement in 1956 and the indicated year. Thus, the point plotted at 28 km downstream for 2000 represents the entire volume evacuated between the dam and the cross section 28 km downstream for the period from 1956 to 2000.

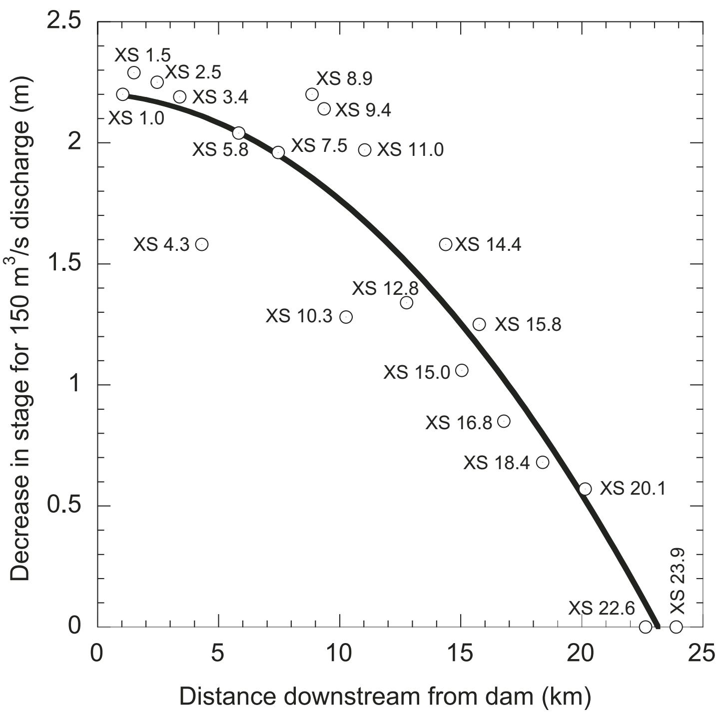


Figure 11. Change in stage between 1956 and 2000 at a discharge of 150 m³/s, plotted as a function of distance downstream from Glen Canyon Dam.

Channel Incision and Development of the Post-dam Longitudinal Profile

Channel incision occurred contemporaneously with sediment evacuation before and during the 1965 pulsed flows; although, evacuation continued well after widespread incision had ceased (Fig. 10). Most of the sediment evacuated from Glen Canyon was derived from pools. On average, erosion at pools exceeded that measured in riffles by a factor of five. However, only the erosion of bed material from riffles, the hydraulic controls, results in channel incision. The magnitude of incision decreased systematically with distance downstream from Glen Canyon Dam, but sediment evacuation from pools was as great near Lees Ferry as near the dam (Fig. 7).

Incision of riffles caused downward shifts in stage-discharge relations from the dam to cross sections 20 km downstream from the dam. Most of these shifts had occurred by September 1965 and were clearly related to the large-scale bed incision. Between 1956 and 2000, water-surface elevations for a reference discharge of 150 m^3/s decreased by more than 2 m at the upstream end of the study area but were unchanged 24 km downstream at XS 23.9 (Fig. 11). This widespread change in the water-surface profile indicates that all riffles upstream from XS 20.1 have been incised, while riffles downstream from XS 20.1 have been stable (Fig. 7). This longitudinal pattern of incision caused the reach-average gradient to decrease by ~25%, from 0.0004 to 0.0003 at a reference discharge of 150 m^3/s (Fig. 9).

Predicted Bed Stability

Bed stability analysis indicates that the Colorado River was transformed from an alluvial channel to a threshold channel. We iteratively solved Equations 1, 2, 3, and 4 for the pre-dam and post-dam 2 yr recurrence flood, study-area average gradient, and study-area average width. We represented the pre-dam bed grain size as that of the gravel subsurface (Fig. 8), because the river scoured to this depth during the annual snowmelt flood, as described above. Comparison of pre-dam and post-dam conditions with those of a threshold channel with similar bed grain size shows that the pre-dam bed was an alluvial channel during the 2 yr recurrence flood (Fig. 12). During the snowmelt floods, sand and finer sediment was transported in suspension and scoured from the bed (Fig. 2A). The gravel that was exposed by scour was smaller than predicted for a threshold channel, indicating that active gravel transport occurred when annual scour was at its maximum. Today, the bed surface is approximately the same grain size as the pre-dam subsurface. Reduction of the gradient

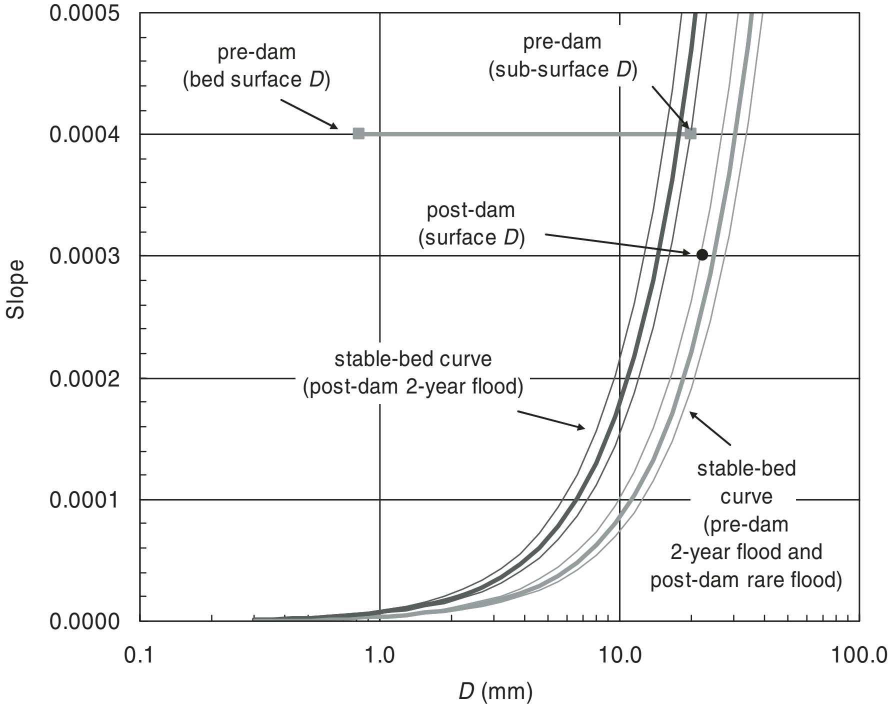


Figure 12. Plot showing curves that define the range of stable reach-average slope and bed-surface grain-size combinations for the pre-dam 2 yr recurrence flood and the post-dam 2 yr recurrence flood. For comparison purposes, the post-dam rare flood is taken to be approximately the same as the pre-dam 2 yr recurrence flood. In each case, a Manning's *n* of 0.025 was used for the thick center line. The upper and lower ranges were defined using a Manning's *n* of 0.02 and 0.03, respectively. In the pre-dam period, the bed surface was much finer than the stable bed curves predict. These measurements were made during the summer when sediment accumulated on the bed in Glen Canyon. Coarsening, possibly to the degree of the pre-dam subsurface, likely occurred during pre-dam floods. The current bed-surface and reach-average slope are within the range predicted by the bed stability curves.

has been sufficient to reduce τ such that the bed no longer scours during annual floods and transport during normal years is sustained with very little bed entrainment. The bed probably is entrained only during the rare floods that exceed the capacity of the power plant. Thus, the current grain-size distribution of the bed surface is more closely adjusted to the high flows of the 1980s than average post-dam flows.

Changes in Alluvial Deposits

Large-Scale Attributes of Alluvial Deposits in Glen Canyon

Early photographic records show that sand and gravel deposits were common features in Glen Canyon in the pre-dam period. The largest sand deposits were point bars located inside or downstream from sharp bends (Fig. 1). Smaller sandbars occurred in eddies and discontinuously along the banks (Fig. 5). Gravel deposits occurred mid-channel or as bank-attached bars downstream from bends. Many of the largest gravel bars were downstream from tributary confluences. In the pre-dam period, gravel bars had little to no vegetation and were covered by thin patches of bare sand, indicative of annual reworking by high flows. Historical photographs taken between 1889 and 1956 show fresh deposits of bare sand along the channel margins and on mid-channel bars throughout the study area (Fig. 13). Our mapping of the 1952 aerial photographs shows these same features (Fig. 5). Between Glen Canyon Dam and Lees Ferry,

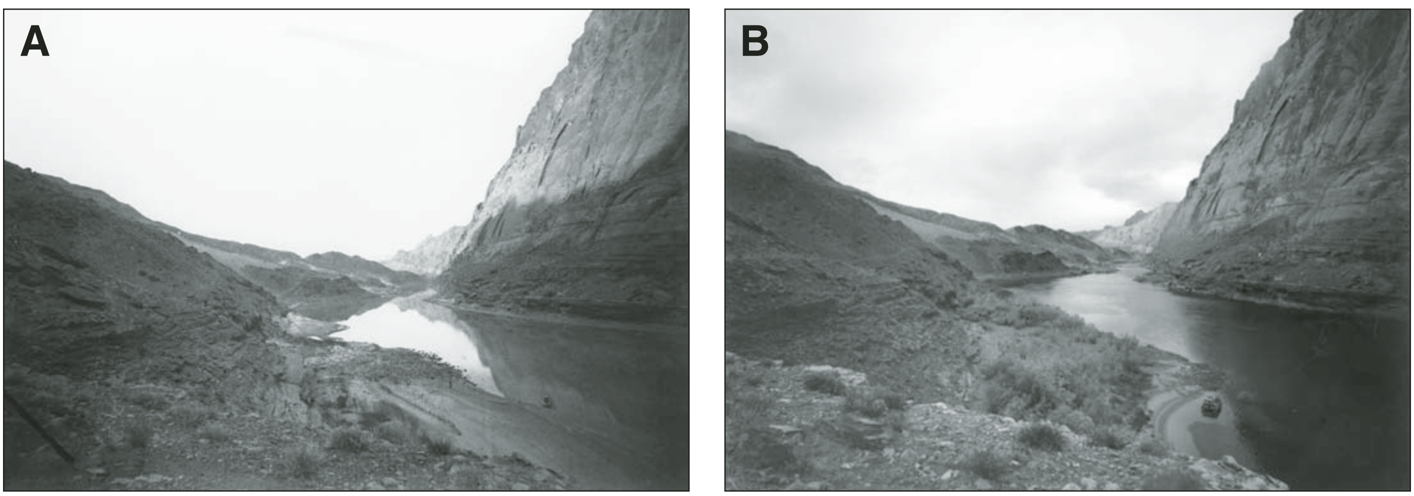


Figure 13. View looking downstream at small debris fan and sandbar on the left bank of the Colorado River ~3 km upstream from Lees Ferry. The approximate location is shown in Figure 1. The original photograph was taken by Robert Brewster Stanton on 26 December 1889 (A). The match was made by Tom Wise on 28 October 1992 (B). The discharge for the date of the original photograph is not known, but the mean daily discharge for the months of December and January in the pre-dam period was 156 m^3/s. Flow at the time of the 1992 repeat was 275 m^3/s. Note the much smaller area of bare sand and much larger area occupied by woody riparian vegetation (tamarisk) in 1992. For scale, the river is about 100 m wide at the constriction. These photographs were previously published in Webb (1996).

55% of the alluvial deposits were fine-grained terraces, 29% were bare sand, and 16% were gravel in 1952 (Fig. 14).

Evidence derived from channel surveys made during discharge measurements at the Lower Cableway shows that some floodplain aggradation and channel narrowing occurred prior to dam construction. Here, there were five periods when the relation between width and water-surface elevation was stable, and each period was separated by an episode of floodplain deposition and channel narrowing (Fig. 15). Deposition occurred primarily during floods when migrating alternate bars became attached to the floodplain and vertically accreted. The first episode of accretion began between 15 June and 22 June 1935, during the spring flood (Fig. 16, depositional event 1); by 12 May 1936, channel width had narrowed by 2.3 m (event 2), creating a channel that was stable until 9 June 1938, when the channel narrowed by an additional 1.4 m (event 3). A final episode of narrowing occurred in May 1948, when vertical aggradation of ~0.5 m occurred and the channel narrowed ~1.8 m (event 4). In total, deposition on the left bank at the Lower Cableway decreased active channel width by ~5.5 m between 1935 and 1957 (Fig. 15). No measurements of topography were made between July 1957 and 2000. The 2000 survey indicates that additional vertical aggradation must have occurred during the 1958 flood, which was the only flood to reach a sufficiently high stage (Fig. 16). These changes are consistent with those reported by Hereford et al. (2000), who showed that up to 50 m of channel narrowing between the 1920s and 2000 occurred in the vicinity of the Paria River, just downstream from the Lower Cableway.

Notes from the Lees Ferry hydrographers' log confirm that channel narrowing began in 1935. On 4 June 1935, the hydrographer noted deposition near and upstream from the gage that was caused by flash floods from nearby tributaries and the subsequent stabilization of those deposits by willow (Fig. DR3, see footnote 1). Both the 1935 and 1952 aerial photographs show a vegetated deposit in this location, although the willow noted by the hydrographer has been replaced by non-native tamarisk (*Tamarix ramosissima*).

Changes in Alluvial Deposits after Dam Construction

On average, active channel width in the study area decreased by 6%, from 156 m to 146 m, between 1952 and 1984. While some of this narrowing may have resulted from deposition between 1952 and dam closure, most was caused by a decrease in the frequency of deposit inundation. In the upstream 20 km of the study area, inundation frequency decreased due to bed incision and decreased magnitude of annual floods. This resulted in the abandonment of some alluvial deposits, an increase in the area of alluvial deposits inundated at discharges between 300 and 600 m^3/s, and an overall narrowing of the active channel (Fig. 1). This is illustrated in the post-dam photographs, which show more gravel bars, more vegetated sandbars, and fewer bare sandbars (Figs. 5 and 6). Post-dam flood deposits that are infrequently inundated have been colonized by riparian vegetation (Figs. 5 and 13), consisting primarily of tamarisk. Although this invasive shrub has been present in the region since the 1930s (Clover and Jotter, 1944), it increased in abundance after 1952 (Turner and Karpiscak, 1980). Despite sediment evacuation, the total area of channel-side and mid-channel sand deposits exposed at flows of similar recurrence has not changed significantly (Fig. 14). However, the proportion of the alluvial valley that is covered by deposits with perennial, riparian vegetation has increased, while the area of bare sand has decreased. Areas of significant erosion are spatially limited. The largest area of erosion between 1952 and 1984 occurred near XS 10.3, where a large part of a pre-dam terrace was eroded (Fig. 6). Thus, with the exception of these isolated areas of erosion (Fig. 1), deposits along the channel margins have maintained or increased stability while the adjacent channel incised.

Channel width also decreased in the post-dam period in the downstream 5 km of the study area where no bed incision has occurred. In this part of the study area, channel narrowing resulted from the decreased magnitude of high flows in the post-dam period and some post-dam deposition. Sediment evacuation has been concentrated in the pools and has occurred despite some bank accretion. This is illustrated by the post-dam changes at the Lower Cableway, where deposition in the post-dam flood zone was documented by the 2000 surveys (Fig. 16). These deposits were likely constructed by the floods of 1962, 1965, 1983–1986, and 1996, and this deposition resulted in a 1.5 m decrease in channel width beyond that measured for the pre-dam period.

The volume of material eroded from channel-side deposits throughout the study area is small compared to the volume of sediment eroded from the bed. We estimate that $3 \pm 1 \times 10^6$ Mg of sediment was eroded from channel-side sand and gravel deposits (based on a specific gravity of 2.65 and a porosity of 35%), equivalent to ~14% of the estimated mass eroded from the bed. This estimate is based on extrapolating the thickness of eroded deposits from the relatively few places where cross-section surveys show

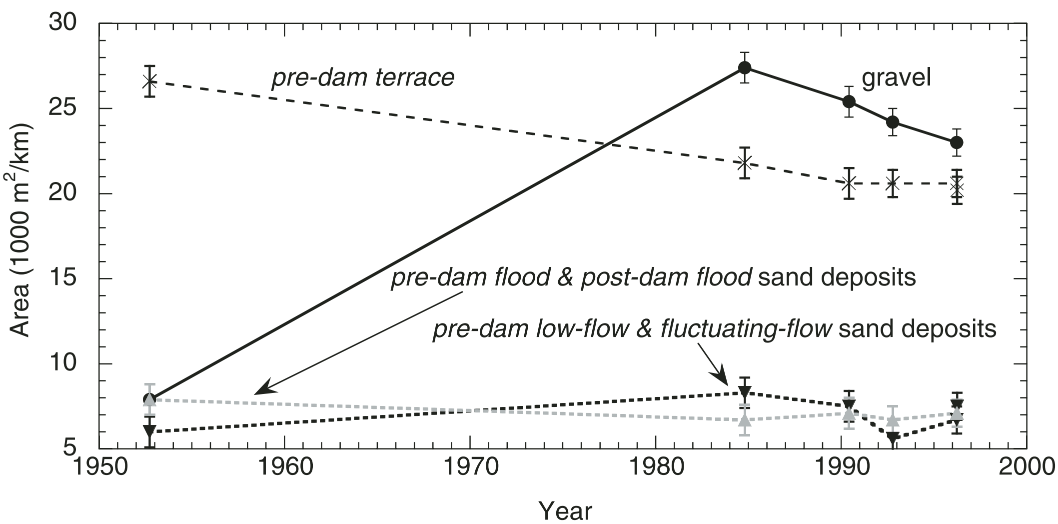


Figure 14. Time series showing trend in the area of sand deposits, gravel deposits, and pre-dam terrace. Despite erosion that has caused decreased elevation of sand deposits and changes in the discharge required for deposit inundation, similar areas of deposits exist at low and high elevations, respectively. The error bars are the standard error about the mean.

eroded pre-dam deposits to all areas where comparison of the 1952 and 1984 photographs showed erosion (Fig. 1). Based on those cross sections, 6 ± 1 m has eroded from pre-dam terraces and 2 ± 1 m has eroded from pre-dam low-flow deposits and pre-dam flood deposits.

DISCUSSION

Timing of Channel Incision

It may seem self-evident that the rate and pattern of downstream channel change are affected by water-resource-engineering decisions, including dam size, reservoir operating criteria, downstream requirements for water delivery, and hydroelectric power generation. Nevertheless, the effects of engineering decisions on the patterns of downstream channel change are often overlooked. For example, Williams and Wolman (1984) proposed a standardized channel incision versus time relation that predicts the rate at which the bed becomes incised downstream from all dams. In many other studies, pre- and post-regulation average flow statistics are used as the primary controlling variable in predicting channel response (e.g., Grant et al., 2003; Brandt, 2000a). Such approaches fail to consider the role of exceptional events and engineering decisions that lead to those events in controlling geomorphic processes.

In Glen Canyon, one of the many case studies summarized by Williams and Wolman (1984), the most rapid episode of channel incision and a disproportionately large fraction of sediment evacuation were caused by the pulsed releases of May 1965, a pattern of dam releases unique in the 43 yr history of dam operations. Not only did these releases scour sediment from Glen Canyon, they also scoured ~16×10^6 Mg of sand, silt, and along from the 141 km stretch between the Lees Ferry and Grand Canyon gaging stations (Topping et al., 2000; Rubin and Topping, 2001). The Bureau of Reclamation predicted bed incision between the dam and Lees Ferry in studies completed prior to dam construction, and these predictions were incorporated into the power plant design (Bureau of Reclamation, 1957). Bureau of Reclamation engineers photographed the river downstream from the dam during the troughs between the flow pulses to monitor the evolution of the hydraulic controls, and, following the pulsed flows, they observed that bed elevations were in good agreement with the design elevations (Fig. DR1, see footnote 1). Thus, the magnitude of sediment evacuation was an unavoidable and anticipated impact of the dam and the deficit conditions that the dam created. However, the timing of the major episode of evacuation was not a general response but rather the result of a unique and site-specific suite of water-resource management decisions.

Management decisions are especially important in determining the rate and magnitude of channel change downstream from very large reservoirs. An important metric for reservoir capacity is the ratio of reservoir volume to mean annual flow. This ratio is 2.3 for Lake Powell, which is much larger than the national average of <1.0 (Hirsch et al., 1990). Operators of dams and reservoirs that have a storage capacity that is large relative to runoff volume have greater flexibility in designing release patterns, storing flood

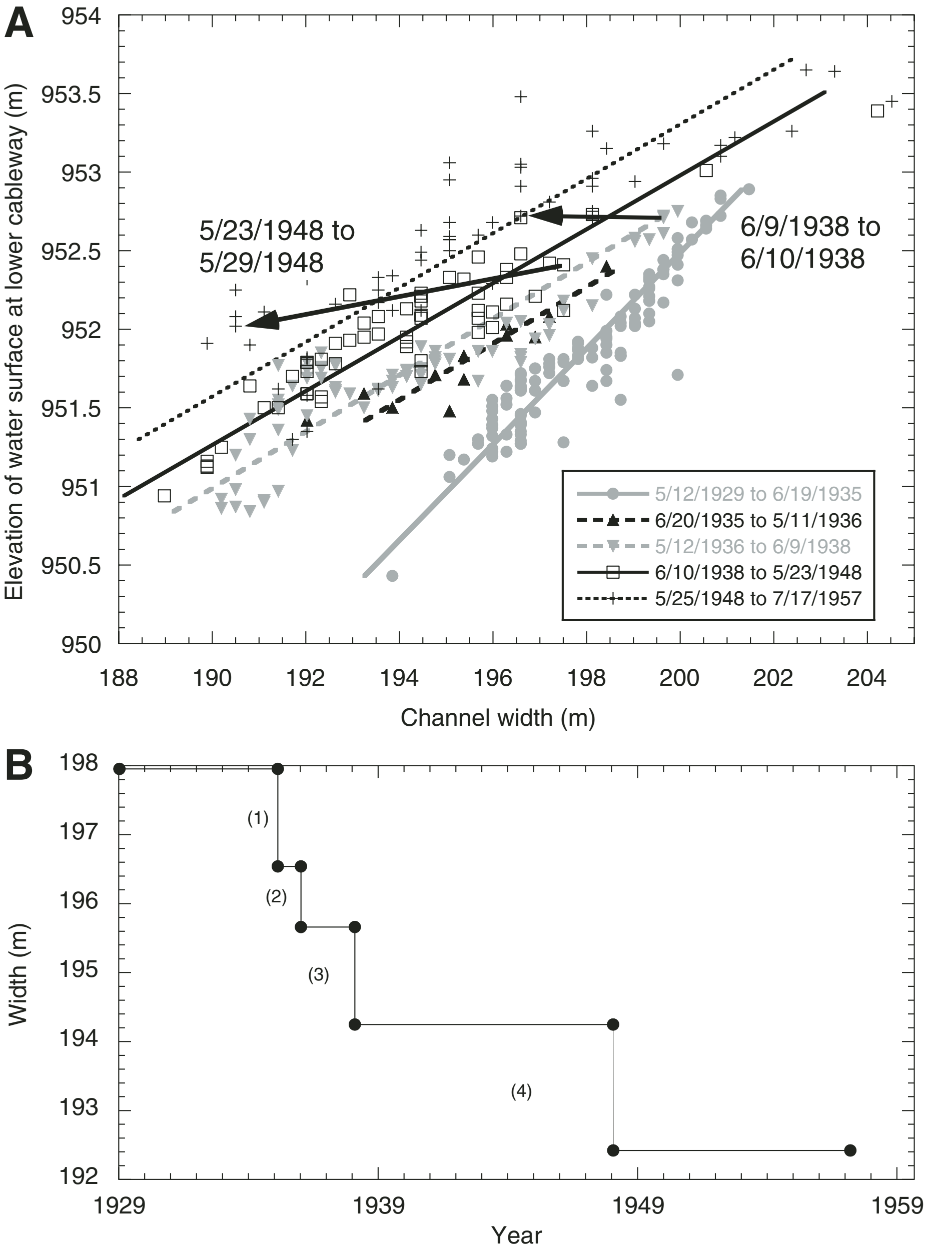


Figure 15. (A) Channel width as a function of water-surface elevation at the Lower Cableway. The data include all Lower Cableway measurements and are divided into five time periods showing episodic decrease in channel width. The data within each time period were fitted by linear regression, which was used to determine the channel width at a common discharge of 2130 m³/s. For 1929 to 19 June 1935, this is at elevation 951.86. After 19 June 1935, this is at elevation 952 m. This discharge was used because it is near the center of the range of measured flows in the pre-dam period. The arrows show two of the rapid episodes of channel narrowing. (B) Channel width as a function of time for a common discharge of 2130 m³/s. The numbers refer to the depositional events shown in Figure 16 and described in the text.

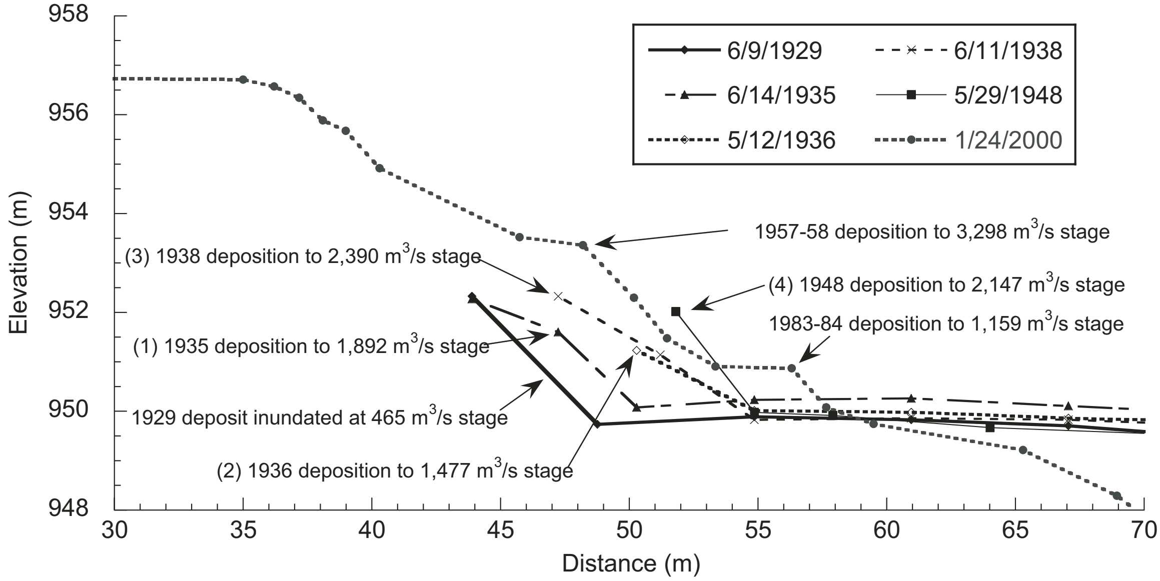


Figure 16. Detail of the left bank of the cross section at the Lower Cableway. The bed elevations are from U.S. Geological Survey discharge measurements. The numbers refer to channel narrowing depositional events shown in Figure 15B and described in the text.

inflows, and routing releases to produce hydroelectricity. The decision to release large floods from Glen Canyon Dam in 1965 was made in response to water-policy concerns, and was not forced by a hydrologic emergency. Thus, the geomorphic trajectory of the Colorado River in Glen Canyon was largely determined by a discretionary operational decision. Had the 1965 pulsed releases not occurred, major bed incision in Glen Canyon would likely have been delayed until the spill releases of the mid-1980s. Thus, when making generalizations about bed changes downstream from dams, factors such as reservoir storage capacity and management decisions must be considered in addition to factors such as inflow hydrology and local geomorphology.

Pattern of Channel Incision

Many studies have reported longitudinal variation in the magnitude of bed lowering caused by local differences in bed texture (Vetter, 1937; Stevens, 1938; Lagasse, 1981; Xu, 1996; Simon et al., 1999). Similar longitudinal variations occurred in Glen Canyon. Pools and riffles were incised to different extents and at different rates, especially during the 1965 pulsed releases. The majority of incision of riffles occurred during the 1965 pulsed flows, and the magnitude of bed lowering progressively decreased downstream. Incision of riffles caused downward shifts in stage-discharge relations, and the magnitude of these shifts also progressively decreased further downstream. In contrast, sediment evacuation from pools was variable and continues to the present. Sediment evacuation from pools occurred even where adjacent riffles did not incise. Immediately downstream from the study area, Schmidt et al. (2004) reported similar patterns of evacuation where sediment has eroded from pools, but there have been no bed elevation changes in adjacent rapids. This difference in behavior between coarse-grained hydraulic controls (riffles and rapids) and other locations (pools) may explain the variability in the magnitude of channel change reported in other case studies.

This variability further complicates the effort to predict the ultimate profile of a regulated river shifted into sediment deficit. In the case of Glen Canyon, the repeat measurements from cross sections show that channel controls have essentially stabilized, but pools temporally accumulate or evacuate sediment depending on dam operations. Accumulation of sediment in pools has occurred during periods dominated by lower power plant discharges, and evacuation has occurred during periods when releases exceed power plant capacity (Fig. 7). The response of the channel controls is predictable, because the response is governed by sediment mobility processes. The behavior of pools is governed by tributary fine-sediment supply, and pool evacuation can be expected as far downstream as deficit conditions persist.

Magnitude of Channel Incision and Predicted Bed Stability

Our analysis of mobility of the gravel bed indicates that although the high seasonal input of fine sediment has lent Glen Canyon the appearance of a sand-bed river, the channel geometry, the size of gravel beneath the sand veneer, and study-area average gradient are typical of a gravel-bed river with active gravel transport. The approach that we used to estimate bed stability predicts the direction and approximate magnitude of adjustment in channel gradient and the creation of the present-day threshold channel. The analysis also demonstrates (1) the relative contributions of bed coarsening and channel incision in creating a threshold channel, and (2) the different magnitudes of likely future adjustment under different flow regimes. In Glen Canyon, future channel incision and coarsening is unlikely if flows do not exceed the capacity of the power plant, but further incision of the riffles might occur during large floods. Gradient may continue to decrease by incision of upstream riffles, because the bed has not coarsened much beyond the range of the pre-dam subsurface grain size. Stabilization of riffles may occur over time, however, from tributary inputs of coarse sediment, similar to those described downstream in the Grand Canyon and elsewhere (Graf, 1980; Webb et al., 1997; Magirl et al., 2005).

Previous investigations of bed adjustment at Lees Ferry (Burkham, 1986; Topping et al., 2000) have focused on the role of the decreasing supply of fine sediment in causing incision and sediment evacuation. However, the pattern of observed bed adjustment in Glen Canyon demonstrates that channel incision and sediment evacuation are distinct processes that may follow separate trajectories in response to different controlling variables. While the gross magnitude of sediment evacuation is clearly related to the magnitude of sediment deficit, the magnitude of bed incision and the pattern of river profile adjustment are determined by the mobility of material in riffles.

The Ecological Implications of Channel Adjustment

The rate of channel change in Glen Canyon has slowed greatly, and many aspects of the channel appear to have adjusted to the regulated flow regime and present tributary sediment supply rates. Although pools may scour and partially refill, the riffles have stabilized. The rate of erosion of channel-side deposits has declined since 1984 and is now partially compensated by deposition. Pre-dam terrace erosion is now minor, and fluctuating-flow and post-dam flood deposits may have already adjusted to the current post-dam flow and sediment regime. Eddy sandbars and channel-margin deposits are largely stabilized by dense thickets of riparian vegetation. These deposits are rarely inundated by dam operations and in many cases are protected by gravel or cobble armor. The persistence of the remaining bare sandbars demonstrates the efficiency of eddies as sediment traps and suggests that the sediment input from the tributaries, however meager, may be sufficient to maintain these deposits.

Nevertheless, the physical transformations described here, especially bed incision and consequent shifts in the stage-discharge relations, have caused widespread ecological changes. In general, these changes have been disadvantageous for the relict, native ecosystem, and they have been advantageous for the artifact, non-native ecosystem (Schmidt et al., 1998). Physical changes include permanent loss of the sand veneer and creation of a threshold gravel channel, erosion of some pre-dam terraces, conversion of most sandbars to gravel bars, and conversion of active gravel bars to inactive bars that are no longer inundated. Deposits that were once within the active channel are now higher than the stage of base flow and are stabilized by perennial riparian vegetation, which is dominated by non-native tamarisk. Pre-dam flood deposits and terraces are now abandoned and may never be inundated, especially where the effect of bed incision compounds the effect of lowered flood frequency. In these places, pre-dam riparian vegetation communities have shifted to upland ecosystems (Turner and Karpiscak, 1980; Ralston, 2005). The evacuation of fine sediment from the bed combined with low concentrations of suspended sediment have transformed the aquatic system from one dependent on upstream supply of nutrients and carbon to an autotrophic system where the foundation of the food base is in-stream growth of algae (Kennedy and Gloss, 2005). This food base supports non-native trout that thrive in the cold temperatures, gravel bed, clear water, and relatively stable flows of the post-dam river (Gloss and Coggins, 2005).

CONCLUSIONS

Closure of Glen Canyon Dam resulted in a 63% decrease in the magnitude of the mean annual flood and a 99% decrease in the annual sediment load in Glen Canyon. These changes resulted in sediment deficit, channel incision, and bed-sediment evacuation. The highest rate of bed lowering occurred in 1965 during a series of pulsed high dam releases. The magnitude of bed lowering was predicted prior to dam construction and is consistent with our analysis of pre- and post-dam bed stability. While the magnitude of channel incision was a predictable physical process, the rate and timing of lowering was determined by management decisions relating to dam operations. The magnitude of incision in hydraulic controls, such as riffles, decreased with time and also decreased predictably downstream, resulting in a lower post-dam reach-average gradient. In contrast, sediment evacuation from pools was spatially and temporally variable, extended downstream from the study area, and continues to occur during high flow events. The average bed-material grain size in Glen Canyon increased from ~0.25 mm to ~20 mm. The adjustment of bed-material grain size and reach-average gradient is consistent with the transformation of an adjustable-bed alluvial river to a stable channel with an infrequently mobilized bed.

Bed incision and downward shifts of stage-discharge relations coupled with decreased flood magnitude have caused limited sandbar and terrace erosion and widespread transformation of active sandbars and gravel bars to abandoned deposits that are no longer inundated by typical post-dam flows. These deposits are above the low-discharge water-surface elevation and are stabilized by riparian vegetation. In the downstream part of the study area where channel controls have not incised, channel narrowing has been caused by decreased flood magnitude, minor post-dam deposition, and vegetation encroachment. These physical changes to the aquatic and riparian environments in Glen Canyon have supported the establishment and continued success of a largely non-native ecosystem.

These results suggest that the rate and pattern of channel response downstream from large dams can be substantially affected by differential response among different channel elements, such as riffles and pools, and exceptional flows resulting from management decisions, such as the pulsed flows in Glen Canyon. Models for channel response to dams should, therefore, include factors such as channel organization and extreme events in addition to the more common factors, such as the degree of sediment deficit, the pre-dam surface and subsurface grain size, and the magnitude of post-dam average flows.

ACKNOWLEDGMENTS

This work was made possible by support from the Grand Canyon Monitoring and Research Center of the U.S. Geological Survey. In particular, Ted Melis initiated the resurvey of the channel in Glen Canyon that got this project started. Reviews of earlier drafts by Amy Draut, Gordon Grant, Ted Melis, Jim O'Connor, Tim Randle, M. Gordon Wolman, and one anonymous reviewer resulted in substantial improvements to the manuscript and are gratefully acknowledged. We also thank Robert H. Webb for the generous access to his historical photograph archives.

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Manuscript Received 17 January 2006
Revised Manuscript Received 9 November 2006
Manuscript Accepted 28 November 2006

Printed in the USA